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Cognitive Development 19 (2004) 203–222

COGNITIVE DEVELOPMENT

Modes of knowing and ways of reasoning in elementary astronomy

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Received 30 June 2003; received in revised form 30 November 2003; accepted 20 December 2003

Abstract

An experiment investigated how methods of questioning affect children's responses regarding the shape of the earth and the day/night cycle. Seventy-two children from Grade 1 and Grade 3 in a middle-class elementary school in Athens, Greece, were tested either by an open method of questioning or by a forced-choice method of questioning. The two methods of questioning produced different results, suggesting that they tap different forms of knowing and encourage different ways of reasoning in elementary astronomy. The open method replicated previous findings by Vosniadou and Brewer [Cogn. Psychol. 24 (1992) 535], showing that the majority of the children gave responses consistent with a small number of internally consistent mental models of the earth. The forced-choice method of questioning produced an increase in scientifically correct responses, but also a decrease in internal consistency. It appears that the forced-choice method of questioning, together with the presentation of the spherical model of the earth, can inhibit the generation of internal models.

Keywords: Cognitive development; Conceptual change; Reasoning; Elementary astronomy

1. Introduction

In a series of studies that investigated the development of children's cosmological knowledge, Vosniadou and Brewer (1992, 1994) showed that young children had considerable difficulty in understanding the scientific concept of the earth as a rotating sphere whose revolution around the sun causes the day/night cycle. Although most of the children knew

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0885-2014/$ – see front matter
doi:10.1016/j.cogdev.2003.12.002

that the earth is round, they also believed that the earth has an end/edge from which people can potentially fall off, and thought that people cannot live at the "bottom" of the earth. Detailed examinations of the individual children's responses showed that a great deal of the apparent inconsistency could be explained by assuming that the children had used in a consistent fashion a mental representation, a mental model, of the earth that was different from the spherical earth model.

Five alternative models of the earth were identified in the U.S. data: the rectangular earth, the disc earth, the dual earth, the hollow sphere, and the flattened sphere. With the exception of the flat/rectangular earth model, which appears only in the case of the youngest children, all the remaining models were similar in two respects: (a) they portrayed the earth as both round and flat, and (b) the children believed that people live on flat ground either above the top of the earth or deep inside a hollow earth. These results were interpreted to suggest that alternative models of the earth are *synthetic* models, derived from children's attempts to assimilate the scientific information that the earth is a sphere to an initial concept of a flat, stable, supported earth. More specifically, it was hypothesized that the robustness of the initial concept is derived from the fact that young children categorize the earth as a physical (rather as an astronomical) object and apply to it the presuppositions that are appropriate for physical objects in general (i.e., solidity, stability, up/down organization of space, up/down gravity, etc.). These presuppositions then act as constraints on the knowledge acquisition process and influence the interpretation of the scientifically accepted information about the earth (Vosniadou, 1994, 2002).

Subsequently, several cross-cultural studies were conducted in Samoa (Brewer, Hendrich, & Vosniadou, 1987), in India (Samarapungavan, Vosniadou, & Brewer, 1996), in Greece (Vosniadou, Archontidou, Kalogiannidou, & Ioannides, 1996), and with native Indian-American children in South Dakota (Diakidoy, Vosniadou, & Hawks, 1997). These studies showed that young children in different parts of the world form alternative models of the earth that reveal the presuppositions of flatness and support, but are also influenced by native culture (Vosniadou, 1994). Additional cross-cultural studies confirmed both the persistence of presuppositions of flatness and support as well as the influence of culture on the development of children's cosmological knowledge (e.g., Blown, 2001; Mali & Howe, 1979; Nussbaum, 1979; Nussbaum & Novak, 1976; Sadler, 1992; Sneider & Pulos, 1983).

Recently, new research has come to challenge some of the findings of the studies conducted by Vosniadou and her colleagues (Ivarsson, Schoultz, & Saljo, 2002; Nobes et al., 2003; Schoultz, Saljo, & Wyndhamn, 2001; Siegal, Butterworth, & Newcombe, in press). Schoultz et al. (2001) and Ivarsson et al. (2002) argued that not enough attention has been paid to socio/cultural influences on the development of children's understanding of the shape of the earth. In their studies, children presented with the appropriate cultural artifacts (i.e., a globe) appeared to understand the spherical shape of the earth without difficulty. Siegal et al. (in press) found that Australian children were significantly in advance of British children in producing responses compatible with the scientific model. They concluded that Vosniadou and Brewer (1992) used methods that underestimated children's cosmological knowledge and argued that the Australian children, having been exposed to cultural information early on, showed no evidence of the presuppositions of flatness and support. Finally, Nobes et al. (2003) compared British and Gujarati children (from the state of Gujarat in India, but living in London) and found no evidence for initial or synthetic models of the earth. They concluded that children's knowledge is fragmented and unsystematic, rather than guided by mental models.

A common characteristic of the studies that are critical of Vosniadou and Brewer (1992) is that they either used a forced-choice method of questioning (Nobes et al., 2003), or they presented the children with a spherical model of the earth (Schoultz et al., 2001), or both (Siegal et al., in press). The forced-choice method of questioning is problematic for various reasons. First, it has the potential of biasing children towards the socially acceptable, scientifically correct responses to which they may have been exposed but which they may not fully understand. For example, when the children are asked to explain the day/night cycle in the Open Questionnaire, they are asked a general question of the sort "Can you explain how it changes from day to night?" In the Forced-Choice Questionnaire they are asked instead to choose between two possible alternatives, one of which is the scientifically correct one. All that the children have to do in the latter case is to recognize the scientific alternative, a simpler and easier task than the generation of the scientific explanation.

A second problem with the forced-choice method of questioning is that it limits the range of responses available to children, thus masking the possible existence of synthetic models. For example, while in the Open Questionnaire the children are asked to draw the earth, or to construct their own model of the earth, out of play-dough, in the Forced-Choice Questionnaire they must only select one of three ready-made models of the earth.

The practice of presenting a spherical model of the earth or a globe to the children during the interview is also questionable because the presence of the spherical model communicates the presupposition that the earth is spherical. In addition, some of the most difficult questions in the open method of questioning, such as the question "Can people live at the 'bottom' of the earth?" can be read off directly from the external model. For example, the children in the Schoultz et al. (2001) study checked to see if there was a country at the location where the toy figure was placed on the globe when this question was asked, and possibly because they saw a country there, answered in a positive manner.

The central goal of all of these studies was to test the Vosniadou and Brewer (1992) claims that children have difficulty understanding the spherical shape of the earth and form synthetic models instead. However, the use of methods that biased children in favour of the scientifically correct responses and masked the existence of synthetic models seriously questions the validity of these tests.

Siegal et al. (in press), following Siegal (1991), claim on the contrary that the open method of questioning may mask children's early competencies in this domain, as Piaget may have underestimated children's early competencies in his conservation tasks. More specifically, Siegal et al. (in press) noted two possible methodological problems with the open method of questioning. One is the problem of repeated questioning. In some cases, under the open method of questioning, the children were repeatedly questioned on a theme, a practice that has been shown to lead to inconsistency, as children change their minds to comply with the implicit demands of the experimenter's questions.

We are in complete agreement with Siegal (1991) that children are highly sensitive to the social requirement implicit in experimental situations and that they may change their responses in conditions of repeated questioning to comply with the implicit demands in the questions. However, as we had noted in our original experiments (Vosniadou & Brewer, 1992), had that been the case, it would have led to the conclusion that our studies underestimated consistency in the response patterns of the children in our sample, who were in fact highly consistent. Indeed, it is our critics (Nobes et al., 2003; Siegal et al., in press) who find inconsistency in children's responses about the earth and the day/night cycle, using the forced-choice method of questioning.

Another possible criticism is that the consistency in our data was a product of some implicit bias in our questioning. In other words, alternative models of the earth may not be real, but may be fabricated by the children who yielded to the implicit assumptions in our questions. However, we note (Vosniadou & Brewer, 1992) that this type of bias is extremely implausible. There cannot be any implicit assumptions in our open questions that could give rise to the range of alternative models of the earth that we obtained, with the probable exception of the flat earth model, which was adopted by only two children. On the contrary, there is plenty of room for question bias in the forced-choice method of questioning, leading children to the adoption of the socially accepted and desirable, spherical earth model.

A second methodological critique of the Vosniadou and Brewer's (1992) study is their use of drawings. Siegal et al. (in press) claim that the use of drawings encouraged flat representations of the earth in the Vosniadou and Brewer study. It is hard to say what the effect of drawings may be exactly without specific studies. What we can say with certainty is that the Vosniadou and Brewer (1992) results have been replicated in studies where children were not asked to draw the earth but to construct three-dimensional models of the earth using play-dough (e.g., Samarapungavan, Vosniadou, & Brewer, 1996; Vosniadou et al., 1996).

Behind this methodological debate there are important theoretical differences, as well as theoretical misunderstandings, that center around two basic issues in developmental research. The first concerns the role of cultural information in development and the second the nature and role of mental models.

With respect to culture, our critics think that Vosniadou and Brewer (1992) believe that "young children's understanding of the earth is accomplished solely through a process of direct observation and individual construction" (Nobes et al., 2003, p. 72), and that the presuppositions of flatness and support are based on such observations, as opposed to cultural information that comes later on. They argue instead that cultural information comes early on and that in can influence children's understanding of the earth "directly," before any presuppositions of flatness and support have any chance of being established (Siegal et al., in press).

Our counter-argument is also that cultural information comes early on and that children's beliefs and presuppositions are based not only on observational information but on cultural information as well (Vosniadou, 1994). We do not commit ourselves on the origins of the presuppositions of flatness and support. These could be based on infants' observations, they could be suggested by lay culture, they could be innate (Spelke, 1991), or there could have some combination of these different possibilities.

We differ from our critics in two important respects. First, we make a distinction between lay culture, to which children are exposed from birth on, and scientific information, which often comes in conflict with everyday culture and to which children may not be exposed until they go to school. Vygotsky (1962) noticed these differences a long time ago and argued that the development of scientific concepts follows a different course than the development of everyday concepts. Indeed, young children are often exposed to cultural explanations of the day/night cycle, such as that "the sun sets behind the mountains or rises from the east," or hear everyday talk consistent with the presupposition that unsupported objects fall "down," that come in conflict with scientific views about the earth and the day/night cycle.

In our studies, we are interested in investigating the development of the *scientific concept* of the earth and explanations of the day/night cycle, and not of everyday culture. We hypothesize that children's prior beliefs, based both on observational information and on everyday culture, may stand in the way of understanding the scientific information that comes later on and is counter-intuitive. After all, it took hundreds' of years of scientific work for our culture to come to terms with the idea that our earth is a rotating sphere that revolves around the sun (Kuhn, 1957, 1970).

The second area of difference centers on the mechanisms of internalization of cultural information. We believe that the internalization of the scientific concept is not a "direct cultural transmission," but a constructive process during which the information that comes from the culture can be distorted in the process of being made consistent with what the child already knows. This leads us to a distinction between different modes of knowing, ranging from the simple repetition or recognition of scientific facts to the generative use of scientific concepts. This is not a clear-cut dichotomy but a process of learning science, which often proceeds through the creation of synthetic models or misconceptions (e.g., Novak, 1987).

The above-mentioned theoretical differences influence the choice of methods one adopts to study cognitive development and the knowledge acquisition process. From our perspective, the forced-choice method of questioning and the use of an external spherical model of the earth are problematic because they simply test whether children are able to recognize scientific information. Unlike the Piagetian conservation studies, the present case does not involve uncovering some deep underlying cognitive competencies. We are not interested in finding out whether children have been exposed to the scientific information about the shape of the earth and the day/night cycle. We know that they have. Rather, we are interested in finding out whether they fully understand this information. This is why we challenge them with open-ended, generative questions, which require children to be able to make productive use of the scientific information to which they have been exposed.

It is a common finding in the educational psychology literature that information that comes in from instruction is often only superficially memorized and can be used in limited situations, a phenomenon known as inert knowledge (e.g., Bereiter, 1984; Bransford, Franks, Vye, & Sherwood, 1989). Science educators have also noticed students' higher performance in tests that resemble the information taught compared to their performance in examinations that pose critical questions that require generative problem solving (see Feinman, 1997). A central question in studies of conceptual development and of learning science is about the sources of difficulty in students' understanding of science concepts and the reasons behind the formation of misconceptions (Novak, 1987). In addition to its theoretical interest, such research can have important educational implications.

The Vosniadou and Brewer (1992, 1994) work has also been interpreted as suggesting that children have stable and permanent mental models of the earth. This interpretation may be due to the fact that there are distinctly different views on the nature and status of mental models in the psychological literature (e.g., Brewer, 2003; Gentner & Stevens, 1983; Johnson-Laird, 1983; Vosniadou, 2002). However, Vosniadou and Brewer clearly state that they use the construct of the mental model to denote "a dynamic structure which is created *on the spot* for the purpose of answering questions, solving problems, or dealing with other situations." (Vosniadou & Brewer, 1992, p. 543).

A mental model, is a situation-specific representation, and is constructed to help an individual reason in novel areas where the answer is not known and where there are no external models to be used as representational aids (Vosniadou, 2002). In our studies, the formation of a mental model is encouraged through the use of open-ended and generative questions and also by asking children to draw or construct three-dimensional models of the earth using play-dough. From our point of view, the presentation of a globe discourages children from constructing their own model and encourages them to reason instead on the basis of the cultural artefact presented. Under such conditions, it is unlikely that one will find great support for the construction of synthetic models. According to our hypothesis children will adopt the spherical model presented to them, but will make mistakes when asked questions that are not completely determined by the cultural artefact presented. In this latter case, a decrease in internally consistent responses would be expected.

1.1. The present study

The purpose of the experiment reported in this paper is to compare the forced-choice and open methods of questioning in ways that avoid some of the methodological problems of previous research. Siegal et al. (in press) also compared the forced-choice and open methods of questioning, but they asked the children to draw the earth instead of using three-dimensional models of the earth. In the present study, the children in the open method of questioning were asked to construct their own three-dimensional models of the earth and of the day/night cycle using play-dough, while in the forced-choice method they were asked to select from a predetermined set of four models.

Some additional methodological problems were overcome in our use of the forced-choice method of questioning. We argue that these problems account for some of the failures of the research by Siegal et al. (in press) and Nobes et al. (2003) to find internal consistency in their data. For example, the method of scoring responses as "correct" (scientific) or "incorrect" forces grouping children into "scientific" or "flat" categories, but does not capture nuances that could provide information about the synthetic models that children may have formed. The lack of justification questions accentuates this problem. Unjustified "yes" or "no" responses do not provide adequate information for understanding children's beliefs and can lead to erroneous classification of children's responses as "scientific." Third, the kinds of associations between responses that Siegal et al. (in press) and Nobes et al. (2003) expected in order to classify children in the different synthetic model categories were simply wrong. Last, the Nobes et al. (2003) study is particularly problematic because only four forced-choice questions were used.

It was predicted that the forced-choice method of questioning would produce more scientifically correct responses than the open method of questioning because it tests children's recognition of scientific information and not their ability to use this information generatively. It was also predicted that the forced-choice method of questioning would result in a decrease in the overall internal consistency of responses compared to the open method of questioning because it inhibits the generation of alternative mental models of the earth. Finally, it was predicted that regardless of the type of questionnaire used, children's responses would reveal the same difficulties in understanding the spherical shape of the earth and scientific explanations of the day/night cycle as those found in the previous studies conducted by Vosniadou and colleagues. These would reveal children's presuppositions of flatness and support.

2. Method

2.1. Participants

Our sample consisted of 72 Greek children, students in three middle-class schools in central Athens. Thirty-eight children attended Grade 1 and ranged in age from 5 years and 5 months to 7 years (mean age 6 years and 3 months) while the remaining 34 children attended Grade 3 and ranged in age from 8 years and 5 months to 9 years and 5 months (mean age 8 years and 9 months).

2.2. Materials

The children were randomly divided in two groups. The first group was examined using a Greek translation of the Forced-Choice Questionnaire (FCQ) based on that used by Siegal et al. (in press) and Nobes et al. (2003), while with the second group we adopted a modified version of the Open Questionnaire (OQ) used by Vosniadou and Brewer (1992), to include only the questions used in the FCQ. The two questionnaires were similar to each other, except in their open or forced-choice aspects. Both questionnaires are shown in Table 1. Since previous studies have shown no significant differences in the use of the term "earth" as compared to the term "world," only the term "earth" was used (Siegal et al., in press).

In the OQ task the children were given colored play-dough, which they used to construct models of the earth, the sun, and the moon. In the FCQ task, the children selected one of four pre-constructed play-dough models of the earth, about 10 cm in diameter, representing a round earth, a truncated sphere, a ring earth, and a flat earth. The model of the ring earth was added to the other models used in the Siegal et al. (in press) studies because it has been found to be a popular model with the Greek children (Vosniadou et al., 1996). All play-dough models are shown in Photograph 1.

2.3. Procedure

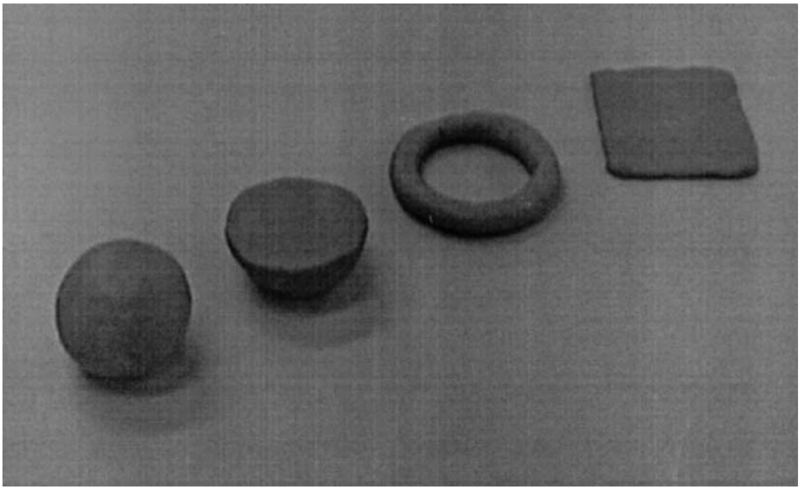
The children were interviewed individually at school by two experimenters. The interviews lasted approximately 15–20 min for each child. All interviews were audio-recorded and were later transcribed for scoring. Detailed notes were also kept during the interview while children's play-dough models were all photographed.

2.3.1. Forced-Choice Questionnaire

The first three questions were asked without reference to physical models. In Q4, the four pre-constructed play-dough models of the earth (shown in Photograph 1) were presented and the children were asked to point to the one that shows how the earth really is. Then,

Table 1
Questionnaires

Forced-Choice Questionnaire	
1	(a) Is the earth round or flat? (b) If it's round/flat, does it look like a circle or a ball?
2	How do you know that the earth is round/flat?
3	(a) If you walked for many days in a straight line, would you fall off the edge of the earth? (b) Why/why not?
4	Look at these models. (*The child is shown four pre-constructed play-dough models of the earth*.) Here is a round ball. Here is half of a ball. Here is a ring, and here is a flat surface. Can you point to the model that shows how the earth really is?
5	(*The alternative models of the earth are removed leaving only the round earth play-dough model*.) (a) This little girl has a sticky stuff on her. You can put her here (top), here (side), or here (bottom). (b) Show me using the little girl where the people in Australia live on the model.
6	(a) Can people live up here? (b) Can they live down there? (c) Show me where people in Greece live.
7	Some children think that the sky is all around; other children think that the sky is only on top. Point to where the sky really is.
8	I have another ball here. Let's pretend this is the sun. When the sun shines on this part of the earth, is it day or night on the other part?
9	When it shines on the other part of the earth, is it day or night on this part?
10	Some children say that day happens because the sun goes underneath the earth and comes up to shine in front of the other part. Some other children say that day happens because the earth turns around so that the sun only shines on one part of the earth at one time. What do you think?
11	I have another ball here. Let's pretend this is the moon. When the moonlight shines on this part of the earth, is it day or night on that part?
12	When it shines on the other part of the earth, is it day or night on this part?
13	Some children say that night happens because the moon goes down in front of one part of the earth and comes up underneath to shine in front of the other part. Some other children say that night happens because the earth turns around so that the moon only shines on one part of the earth at one time. What do you think?
14	(*The child is presented again with the four play-dough models of the earth*.) What is the shape of the earth? Show me the best model.
Open Questionnaire	
1	(a) What is the shape of the earth? (b) If the earth is round, does it look like a circle or a ball?
2	How do you know that the earth is . . . (*use child's words*)?
3	if you walked for many days in a straight line, where would you end up? Is there an end or an edge to the earth? Would you ever reach the end/edge of the earth? (b) Would you fall off that end/edge? Why?/Why not?
4	Take this play-dough and make a model of the earth, as you think the earth really is.
5	(*The following questions are asked on the basis of the play-dough model of the earth that the child has made*): (a) Pretend this is a little girl. If she lived on the earth, where would she live? (b) If this is little girl lived in Australia, show me exactly where she would live.
6	Can people live up here? (b) Can they live down there? (c) Show me where the people in Greece live.
7	Show me where the sky really is.
8	Take this play-dough and make a model of the sun. Pretend this is the earth and that is the sun. When the sun shines on this part of the earth, is it day or night in the other part?
9	When the sun shines on the other part of the earth is it day or night on this part? (*This question is asked only for sphere models of the earth*.)
10	(a) Can you tell me how day and night happen? (b) Does the sun move? (c) Does the earth move? (d) What do you think?
11	(a) Take this play-dough and make a model of the moon. (b) Pretend that this is the earth and this is the moon. When the moon shines on this part of the earth, is it day or night on the other part?
12	When the moon shines on the other part of the earth, is it day or night on this part? (*This question is asked only for the sphere models of the earth*.)
13	(a) Explain to me how day and night happen. (b) Does the moon move? (c) Does the earth move? (d) What do you think?
14	What is the shape of the earth?



Photograph 1. The four pre-constructed play-dough models of the earth used with the Forced-Choice Questionnaire.

the play-dough models of the earth were removed, leaving in sight only the spherical earth model. The remaining questions were asked with reference only to the spherical earth model, as in the original Siegal et al. (in press) studies. In Q5, the children were shown a little doll figure and were asked, with reference to the spherical earth model, to place her "where the people in Australia live." In Q6 the experimenter placed the little doll figure above the top of the spherical earth model and asked the children "Can people live up here?" and then placed it at the bottom of the spherical earth model asking children "Can people live down there?" Finally, the children were asked to take the doll figure and indicate "where the people in Greece live."

For Questions 8–13, in addition to the spherical earth model, the children were presented with two 10 cm play-dough balls, a yellow one for the sun and a silver one for the moon. Finally, for Q14, the four alternative pre-constructed play-dough models of the earth were presented again and the children were asked to point once more to the best model. The purpose of this question was to determine whether the children had changed their model of the earth during the interview.

2.3.2. Open Questionnaire

For the OQ group, the original Vosniadou and Brewer (1992) questionnaire was modified so as to correspond to the Siegal et al. (in press) Forced-Choice Questionnaire. The questions retained of course their open-ended format, and were translated in the Greek language. In Q4 the children were not asked to select one of four pre-constructed models of the earth as in the FCQ task, but to construct their own model using play-dough. Questions 5, 6, and 7 were asked with reference to the child's own constructed model and not with reference to a spherical earth model as in the FCQ task. Questions 8–13 asked children to construct models of the sun and of the moon using play-dough and to use them to explain the day/night cycle, always with reference to their own constructed model of the earth.

3. Results

3.1. Differences in the frequency of responses between the OQ and the FCQ tasks

There were no significant differences in the frequency of children's responses to Questions 1a, 1b, and 2 in the two questionnaires. Question 3 consisted of two parts in the OQ task compared to the FCQ task. In the FCQ task the children were only asked whether they "would fall off the earth," if they walked for many days, while in the OQ, as in the original Vosniadou and Brewer (1992) study, the children were asked first to indicate if "there is an end/edge to the earth" (Q3a), and if and only if they gave affirmative answers, to indicate whether they could fall off this end (Q3b). We hypothesized that the FCQ version would produce more negative answers because children are reluctant to say that they will fall off the earth, even when they do in fact believe that the earth has an end/edge.

The results confirmed this hypothesis. In the OQ task, 53% of the first graders and 41% of the third graders said that there is an end to the earth in Q3a, but when asked whether they can fall off this end in Q3b, only 32% of the first graders and 12% of the third graders, said that you can fall off. The percent negative responses in Q3a in the FCQ task were almost the same as in the Q3b in the OQ (see Table 2). A chi-square that compared the difference in responses between the FCQ Q3b and the OQ Q3a, was very close to being significant at the $P < 0.05$ level [$\chi^2(1) = 3778$, $P < 0.052$], for the third graders.

Q4 in the FCQ task presented children with four play-dough models of the earth and asked them to point to the one that "showed how the earth really is." In the corresponding question in the OQ task, the children were given play-dough and were asked "to make a model of the earth, as you think it really is." The children in the OQ task (and particularly the Grade 1 children) produced a greater variety of alternative shapes of the earth than the ones included in the four alternatives in the FCQ. More specifically, the children in the OQ task created a richer variety of Ring Models (five horizontal rings and two vertical rings),[1] some cylindrical models, and two disks (Table 2). In addition, one child placed in the "round like a sphere" category in the OQ actually made an elliptical sphere. Photograph 2 shows some of the alternative models produced by the children in the OQ task.

Significant differences between the two questionnaires were obtained in children's responses to Q6b. More children in the FCQ condition said that people can live "down there" at the "bottom" of the earth than in the OQ condition [$\chi^2(1) = 4378$, $P < 0.05$, for the first graders, and $\chi^2(1) = 5714$, $P < 0.05$, for both grades]. Also, in Q7, more children said that "the sky is around the earth" in the FCQ condition than in the OQ condition [$\chi^2(1) = 5765$, $P < 0.05$, for the third graders, and $\chi^2(2) = 8014$, $P < 0.05$ for both grades].

As expected, practically all the children knew that when the sun shines it is day and that when the moon shines it is night. The great majority of the children also knew that when it is day in one part of the earth it is night in the opposite part, and the opposite. Thus, Q8, 9, 11, and 12 were not very interesting, compared to Q10 and 13, which asked children to *explain* the day/night cycle. Once more, the results supported our hypothesis showing a

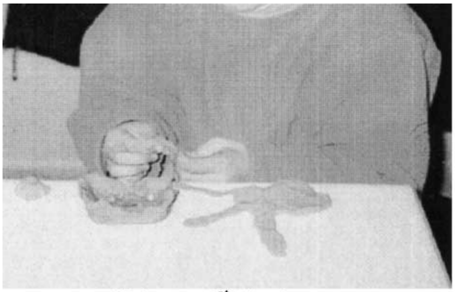
[1] The vertical ring is like the horizontal ring shown in Photograph 2 but the children hold it vertically with respect to the top of the table and place the people inside the ring at the bottom.

Table 2
Children's responses in the Open and Forced-Choice Questionnaire conditions

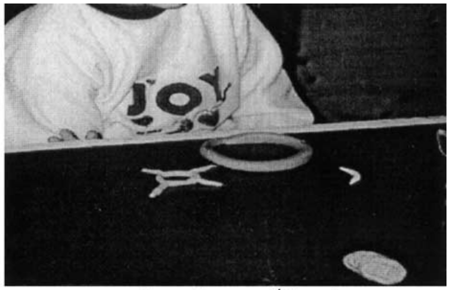
Question	OQ			FCQ		
	Response	Grade 1 (%)	Grade 3 (%)	Response	Grade 1 (%)	Grade 3 (%)
Earth shape						
Q1a	(1) Round	17 (90)	15 (94)	(1) Round	18 (95)	17 (100)
	(2) Circle	1 (5)	2 (6)	(2) Flat	1 (5)	–
	(3) Square	1 (5)	–	–	–	–
Q1b	(1) Like a ball	8 (42)	13 (76)	(1) Like a ball	12 (63)	15 (88)
	(2) Like a circle	10 (53)	4 (24)	(2) Like a circle	7 (39)	2 (12)
	(3) Not asked (square)	1 (5)	–	–	–	–
Q3a	(1) No, there is not an end	8 (42)	10 (59)	–	–	–
	(2) Yes, there is an end	10 (53)	7 (41)	–	–	–
	(3) Don't know	1 (5)	–	–	–	–
Q3b	(1) No, you cannot fall	11 (58)	14 (82)	(1) No, you cannot fall	8 (42)	15 (79)
	(2) Yes, you can fall	6 (32)	2 (12)	(2) Yes, you can fall	11 (58)	2 (12)
	(3) Don't know	2 (10)	1 (6)	(3) Don't know	–	–
Q4	(1) Sphere	10 (53)	14 (82)	(1) Sphere	14 (74)	14 (82)
	(2) Truncated sphere	–	–	(2) Truncated sphere	–	1 (6)
	(3) Ring	4 (21)	3 (18)	(3) Ring	2 (10)	2 (12)
	(4) Flat	1 (5)	–	(4) Flat	3 (16)	–
	(5) Cylinder	2 (10)	–	–	–	–
	(6) Disk	2 (10)	–	–	–	–
Q5b	(1) At the top of the model	3 (16)	7 (41)	(1) At the top of the model	4 (21)	1 (6)
	(2) At the side or at the bottom of the model	10 (53)	9 (53)	(2) At the side of the model	12 (63)	14 (82)
	(4) Don't know	6 (31)	1 (6)	(5) Don't know	3 (16)	2 (12)
Q6a	(1) Yes	17 (90)	16 (94)	(1) Yes	16 (84)	15 (88)
	(2) No	2 (10)	1 (6)	(2) No	3 (16)	2 (12)
Q6b	(1) Yes	1 (5)	9 (53)	(1) Yes	6 (32)	14 (82)
	(2) No	18 (95)	8 (47)	(2) No	13 (68)	3 (18)
Q6c	(1) At the top of the model	15 (79)	11 (65)	(1) At the top of the model	12 (63)	9 (53)
	(2) At the side of the model	1 (5)	2 (12)	(2) At the side of the model	3 (16)	5 (29)
	(3) At the bottom of the model	–	4 (23)	(3) At the bottom of the model	–	2 (12)
	(4) Inside the model	3 (16)	–	(4) Inside the model	–	–
	(5) Don't know	–	–	(5) Don't know	4 (21)	1 (6)

Table 2 (*Continued*)

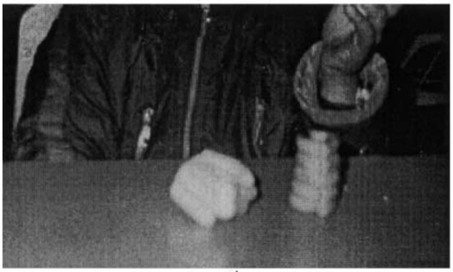
Question	OQ			FCQ		
	Response	Grade 1 (%)	Grade 3 (%)	Response	Grade 1 (%)	Grade 3 (%)
Q7	(1) Around	2 (10)	5 (29)	(1) Around	6 (32)	12 (71)
	(2) Up	16 (84)	12 (71)	(2) Up	13 (68)	5 (29)
	(3) Don't know	1 (5)	–	(3) Don't know	–	–
Day/night cycle						
Q8	(1) Night	17 (89)	16 (94)	(1) Night	18 (95)	17 (100)
	(2) Day	2 (11)	1 (6)	(2) Day	1 (5)	–
Q9	(1) Night	18 (95)	16 (94)	(1) Night	17 (90)	17 (100)
	(2) Day	1 (5)	1 (6)	(2) Day	2 (10)	–
Q10	(1) The earth rotates	2 (10)	7 (41)	(1) The earth rotates	6 (32)	13 (76)
	(2) The sun turns	5 (26)	3 (18)	(2) The sun turns	13 (68)	4 (24)
	(3) Both turn	2 (10)	–	–	–	–
	(4) The earth moves around the sun	3 (16)	6 (35)	–	–	–
	(5) Sun goes behind clouds or mountains, etc.	6 (32)	1 (6)	–	–	–
	(6) Don't know	1 (5)	–	–	–	–
Q11	(1) Day	15 (79)	15 (88)	(1) Day	16 (84)	17 (100)
	(2) Night	4 (21)	2 (12)	(2) Night	3 (16)	–
Q12	(1) Day	15 (79)	15 (88)	(1) Day	15 (79)	16 (94)
	(2) Night	4 (21)	2 (12)	(2) Night	4 (21)	1 (6)
Q13	(1) The earth rotates	4 (21)	6 (35)	(1) The earth rotates	4 (21)	10 (59)
	(2) The moon turns	9 (47)	4 (24)	(2) The moon turns	15 (79)	6 (35)
	(3) Don't know	2 (10)	–	(3) Don't know	–	1 (6)
	(4) Both turn	1 (5)	1 (6)	–	–	–
	(5) The earth moves around the moon	1 (5)	5 (29)	–	–	–
	(6) The moon goes behind clouds or mountains, etc.	2 (10)	1 (6)	–	–	–
Final question						
Q14	(1) Sphere	9 (47)	14 (82)	(1) Sphere	13 (68)	15 (88)
	(2) Truncated sphere	–	–	(2) Truncated sphere	2 (10)	–
	(3) Ring	4 (21)	3 (18)	(3) Ring	3 (16)	1 (6)
	(4) Flat	2 (10)	–	(4) Flat	1 (5)	1 (6)
	(5) Cylinder	2 (10)	–	–	–	–
	(6) Disk	2 (10)	–	–	–	–



Helen – 1st Grade
Overheaded Square–RECTANGULAR EARTH

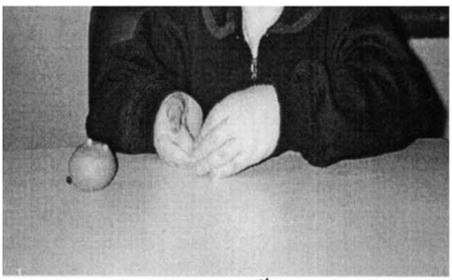


Stavriana – stGrade
Vertical Ring – HOLLOW SPHERE

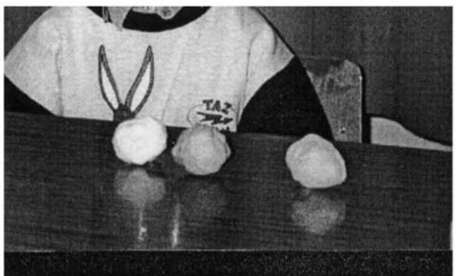


Peter – 1st Grade
Cylinder – HOLLOW SPHERE

Christina – 1st Grade
Flat Disk – DISK



Daphni – 1st Grade
Sphere – SPHERE WITHOUT GRAVITY



Basil – 3rd Grade
Sphere - SPHERE

Photograph 2. Examples of children's models of the earth.

greater number of responses consistent with the scientifically correct answer for the FCQ task, both in the case of the sun [(Q10), $\chi^2(5) = 25{,}811$, $P < 0.05$, for both grades], and in the case of the moon [(Q13), $\chi^2(5) = 13{,}882$, $P < 0.05$, for both grades].

In order to examine the differences between the OQ task and the FCQ task further, each child was given a mark of 2 for every scientifically correct response, a mark of 1 for each alternative earth response, and a mark of 0 for each flat earth response, for all the questions in the questionnaire. The results are shown in graphical form in Fig. 1. The sum of the total scores was subjected to a 2 (grade) × 2 (questionnaire type) ANOVA with repeated measures on questionnaire type. The analysis showed significant main effects both for grade, $F(1, 68) = 41.407$, $P < 0.001$, and questionnaire type, $F(1, 68) = 7689$, $P < 0.01$. The same ANOVA was also conducted using only the earth shape questions (Q1 to Q8). Again, there were main effects for grade, $F(1, 68) = 42{,}107$, $P < 0.001$, and for questionnaire type, $F(1, 68) = 10{,}586$, $P < 0.01$. As hypothesized, the Forced-Choice Questionnaire produced significantly more scientifically correct responses than the Open Questionnaire.

3.2. Differences in the internal consistency of responses between the OQ and the FCQ

In order to see if the children were consistent in their use of a spherical or an alternative model of the earth, we selected, as in the Nobes et al. (2003) study, four questions the answers to which were found in previous studies to critically differentiate amongst the different possible representations of the earth. Table 3 shows the pattern of responses in these four questions that are predicted for the six possible models of the earth. The total number of Response Combinations (RCs) for these questions are 2 for Q1a (round versus circle), 2 for Q3a and Q3b (No/Yes end/edge), 6 flat for Q4 (sphere, cylinder, vertical ring, horizontal ring, disc,) and 2 for Q6b (No/Yes, people can live down there). These make a total of 48 possible RCs. We predicted that instead of the 48 possible RCs we would obtain only 6 RCs, based on the previous findings of our research, corresponding to six relatively well-defined models of the earth: *sphere*, *sphere without gravity*, *hollow sphere*, *dual earth*, *disc earth, and flat/square or rectangular earth*.

The expected pattern of responses to the four questions for the above six models as shown in Table 3, was defined independently of children's obtained responses. For the spherical model, we expected children to say that the earth is round, that it does not have an end/edge, to construct a sphere, and to say that the people can live "down there" at the bottom of the earth. These are all scientifically correct responses.

In the second model, sphere without gravity, we expected children to give responses similar to the sphere model, for all the questions except the last.

Table 3
Models of the earth: pattern of responses

Models	Question 1a	Question 3a/3b	Question 4	Question 6b
Sphere	Round like a ball	No end/edge	Sphere	Yes, people can live "down there"
Sphere without gravity	Round like a ball	No end/edge	Sphere	No, people cannot live "down there"
Hollow sphere	Round like a ball	No end/edge	Sphere/cylinder/ vertical ring	No, people cannot live "down there"
Dual earth	Round/circle	Yes end/edge	Flat model	No, people cannot live "down there"
Disc	Round/circle	Yes end/edge	Horizontal ring/disc	No, people cannot live "down there"
Flat earth	Square/rectangular	Yes end/edge	Flat model	No, people cannot live "down there"

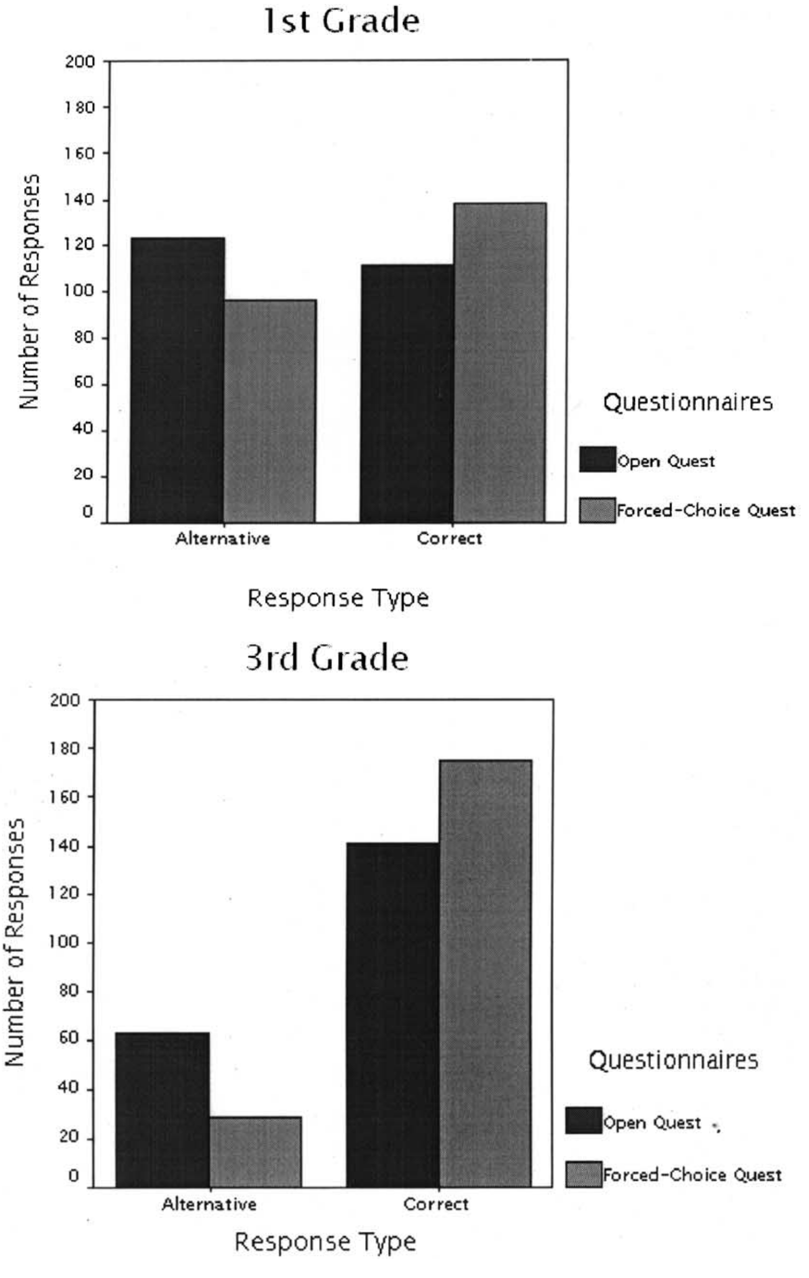


Fig. 1. Number of correct and alternative responses for the Open (■) and the Forced-Choice (▩) Questionnaires.

Table 4
Frequency/percent of subjects placed in the different models of the earth

Models	Open Questionnaire		Forced-Choice Questionnaire	
	Grade 1 (%)	Grade 3 (%)	Grade 1 (%)	Grade 3 (%)
(1) Sphere	0 (0)	8 (47)	3 (15)	12 (70)
(2) Sphere without gravity	5 (26)	2 (12)	8 (44)	0 (0)
(3) Hollow sphere	6 (32)	2 (12)	–	–
(4) Flat disc	4 (21)	2 (12)	–	–
(5) Rectangular flat earth	1 (5)	0 (0)	–	–
(6) Mixed	3 (16)	3 (17)	8 (42)	5 (29)

In the hollow sphere model, we expected children to say that the earth is round and that it does not have an end, to construct either a sphere, a vertical ring, or a cylinder and to clearly say that people live inside the earth, and to also say that people cannot live "down there" at the bottom of the earth.

For the dual earth model we expected children to say that the earth is round but that it has an end/edge. We also expected these children to construct two earth models: a spherical one and a flat earth on which people live.

For the disc earth we expected the children to say that the earth is either round or circle, to construct a flat disc model, to say that the earth has and end/edge and that people cannot live down there, at the bottom of the earth.

For the flat models we expected children to say that the earth is flat, that it has an end/edge, to construct a flat rectangle or square, and to say that people cannot live down there at the bottom of the earth.

Each individual child's responses in the Open Questionnaire task, was checked against the expected pattern outlined above. As Table 4 shows, 47% of the third grade children were placed in the sphere category and the remaining children were placed in sphere without gravity, hollow sphere and disc models (12% in each model). The first grade children were placed in the sphere without gravity, hollow sphere, disc, and flat earth categories (32, 21, and 5%, respectively). There were no dual earth models in the sample. Six children, three from Grade 1 and three from Grade 3, could not be placed in any of the above-mentioned categories. The children who were placed in the hollow sphere model, all said that the earth is round with no end/edge, but constructed a cylinder or vertical ring model to show the earth. They also all said that people cannot live down there under the earth. The children were placed in a disc model if they made a play-dough model of the earth like a disc or a flat square if their model was a square one.

Although the majority of the children in the OQ task could be placed in a well-defined and pre-determined model category, this was not the case for the children in the FCQ task. Following a procedure similar to that used in the OQ task, all the individual children's responses in the FCQ task were investigated to determine if they were consistent with one of the six above-mentioned models of the earth. The results showed that some children gave responses that placed them in the sphere or sphere without gravity categories. However, the remaining children (42% of the first graders and 29% of the third graders) were found to be internally inconsistent. Many of the children who at the beginning of the FCQ task gave responses consistent with an alternative model of the earth, changed some of their answers to agree more with a spherical model when they were presented with a sphere, ending with an overall inconsistent pattern of responses.

4. Discussion

The experiment supported our hypothesis that the two methods of questioning would produce different results. The open method of questioning replicated earlier findings both in terms of the frequency of responses expected in the individual questions and in terms of the overall internal consistency of responses. In the OQ task the great majority of the children (80–85%) gave responses consistent with a small number of internally consistent mental models of the earth. The five, well-defined models of the earth identified were not derived inductively on the basis of the obtained data, as Nobes et al. (2003) have criticized, but were hypothesized independently, on the basis of the results of previous studies. Out of 48 possible RCs, we hypothesized that we would obtain only six. Five of these six hypothesized RCs were obtained, accounting for about 82% of the data. Thus, children's RCs in the OQ task differed significantly from chance, supporting the argument for internal consistency.

The forced-choice method of questioning produced different results from the open method, both in the expected frequency of responses to the individual questions and in the internal consistency of responses. With respect the former, the FCQ task produced more scientifically correct responses than the OQ task. One possible interpretation of this finding is that the OQ task places unduly difficult demands on young children's cognitive capacities, masking early competencies that can be uncovered using the FCQ task. Siegal et al. (in press) favored this interpretation. In their studies they argued that the OQ task underestimated children's cultural knowledge of the earth because they were required to draw the earth instead of selecting a three-dimensional model. Since we did not ask the children to draw the earth but to construct three-dimensional models of the earth, it cannot be argued that children's drawings did not permit them to express their spherical conceptions. Also, it cannot be claimed that the children interpreted the question "Is there an end/edge to the earth?" with reference to the circle that they had drawn to indicate the shape of the earth, because in the present study the children were asked Q3 about the end/edge of the earth, before they were asked to construct (or select) a model.

A different possible reason for the differences between the FCQ and the OQ tasks is that some of the responses in the FCQ task were false positive responses. As was mentioned in the Section 3, some of the negative responses to the falling off the earth question both in the Siegal et al. (in press) and the Nobes et al. (2003) studies cannot be taken as scientifically correct responses, since the children who give them may in fact have the not very scientific idea that there is an end/edge to the earth. We believe that this explanation may account for some of the increase in positive responses in the FCQ task.

A third possible reason is that the FCQ task produced more scientific responses than the OQ because it is mainly a recognition task. It reminds children of the culturally accepted, scientifically correct answers to which they may have been exposed but which they may not fully understand. A clear example of this is the differences between the two questionnaires in children's explanation of the day/night cycle. Only a few children produced the scientific explanation of the day/night cycle in the OQ task but it was the preferred response in the FCQ particularly in the case of the third graders. It appears that children can recognize the scientifically correct alternatives when explicitly presented to them, but have difficulty producing them when they have to reconstruct them on their own, a result with agrees with findings in the educational psychology literature (e.g., Bransford et al., 1989).

With respect to internal consistency, the FCQ task produced markedly fewer internally consistent responses than the OQ, particularly in Grade 1, even though we adopted the same criteria for measuring consistency in the two methods of questioning. More children were found to have scientifically correct models, or spheres without gravity. But all other synthetic models found in the OQ task did not appear in the FCQ. A possible interpretation of this result is that the forced-choice method of questioning, together with the presentation of the external model of the spherical earth, inhibit the generation of internal models and force children to reason on the basis of the socially accepted, scientifically correct model.

This seems to work well for some children, the ones who almost understand the scientific concept, increasing the overall number of internally consistent scientifically correct models in the sample. But it may also confuse the children who cannot incorporate the scientific information in their existing knowledge structures. The latter may end up giving some scientifically correct answers, particularly when these can be implied directly from the external model (thus increasing the overall frequency of scientifically correct responses, as noted earlier), but fail in the more difficult questions, resulting in an overall internally inconsistent pattern of responses.

The example that follows demonstrates some of the difficulties these children may have with the forced-choice method of questioning and the presentation of the spherical model. It comes from the transcribed interview of Angela, a first grader in our sample.

E: Is the earth round or flat? C: Flat.
E: Does it look like a circle or a ball? C: (The child does not respond.)
E: How do you know that the earth is flat? C: That's how I imagine it.
E: If you walked for many days in a straight line, would you fall off the edge of the earth.
C: Yes. E: Why? C: I do not know.
E: Look at these models. Here is a round ball. Here is half of a ball. Here is a ring, and here is a flat surface. Can you point to the model that shows how the earth really is?
C: (The child points to the flat model.)
(The experimenter removes all alternative models of the earth except the spherical model.)
E: This little girl has a sticky stuff on her. You can put her here (top), here (side) or here (bottom). Show me where the people in Australia live on the model.
C: (She puts the figure at the side of the sphere.)
E: Show me where people in Greece live. C: (Shows the top of the sphere.)
E: Can people live up here? C: No. E: Why? C: Because it is round.
E: Down here? C: No. E: Why? C: Because it is upside down.
E: Some children think that the sky is all around. Other children think that the sky is only on top. Point to where the sky really is. C: The sky in reality is only on top.(*At the end of the interview*.)

E: Finally, what is the shape of the earth? Point to the best model.
C: (Child points to the ring model.)

In this example, Angela starts by giving responses consistent with a flat earth model. Then, the model that she selected is removed and she is presented with the spherical model. Angela originally accepts the socially imposed model, but is soon confused with where to place the people. She first places the little girl at the side of the sphere to indicate that this is where Australia is (a response that can be scored as scientifically correct) but later explicitly tells the experimenter that she cannot put the little girl above the top of the sphere "because it is round" or down at the bottom "because it is upside down." At the end she picks up the ring to indicate the shape of the earth. Angela is a clear case of how the forced-method of questioning and the presentation of the spherical model can produce an inconsistent pattern of responses.

Despite the absence of synthetic models in the FCQ task, even a superficial look at children's responses provides ample evidence for the presence of presuppositions of flatness and support. In the FCQ task more than 50% of the first graders placed the little girl above the top of the spherical model and not at the bottom and said that one can fall off the end/edge of the earth, that one cannot live at the "bottom" of the earth, and that the sky is located above the top of the earth. Finally, more than 65% of the first graders selected explanations of the day/night cycle in terms of the movement of the sun or the moon rather than of the earth.

The results of the present experiment add further support to our previous arguments that the internalization of scientific information is not an act of direct cultural transmission but a constructive process of interpretation which can lead to different modes of knowing, ranging from the simple recognition of scientific facts to the generative use of scientific concepts. Different methods of questioning can tap different modes of knowing.

With respect to the question about mental models, the present results replicated previous findings by Vosniadou and Brewer (1992) using the OQ but also showed that the method of questioning one adopts and the presence or absence of external representations can inhibit the generation of internal synthetic models of the earth, thus greatly influencing the way children reason in elementary astronomy.

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