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Cognitive Development 115 (2003) 1–18

COGNITIVE DEVELOPMENT

Conceptual change in physics: children's naive representations of sound

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Received 1 March 2000; received in revised form 1 January 2003; accepted 1 January 2003

Abstract

The organization of physics knowledge (degree of coherence and nature of conceptual change) was studied in 89 6–10-year-old children using the concept of sound. We attempted to determine whether children apply properties of objects to sound or if they consider sounds as a vibratory process. Three properties of physical objects were studied: substantiality, weight, and permanence. The younger children considered sound more like an object than the older children did. Substantiality was attributed to sound more often than were weight and permanence. Based on the substantiality data, four mental models were identified (sound cannot pass through other objects unless there are holes, sound can pass through solids if it is harder than they are, sound is immaterial, sound is a vibratory process). We concluded that conceptual change in knowledge about sound does not happen through the sudden transfer of the concept from the ontological category of matter to the ontological category of processes, but rather through a slow and gradual process of belief revision, in the course of which the various properties of matter are abandoned in a hierarchical order.

Keywords: Conceptual change; Naive physics; Cognitive development

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0885-2014/03/$ – see front matter
doi:10.1016/S0885-2014(03)00018-2

1. Introduction

The purpose of this study was to explore the nature and structure of children's naive knowledge in physics, and more specifically, their understanding of sound. Sound was chosen for two main reasons. The first is that little is known about children's representations of sound; the second is that although sound is an everyday phenomenon it is taught very late in school in France, where the present study took place. This situation therefore offers a good opportunity for studying the naive knowledge that children develop before being influenced by formal instruction in science.

From the scientific point of view, sound is produced by the vibrations of an object that has been struck by some source of energy. These vibrations are propagated through an elastic medium which gradually transmits the state of compression or dilation, without transport of matter. The important point here is that sound is a process of energy transmission and therefore has the physical properties of processes, not those of objects.

According to Piaget (1971), 4–5-year-old children think that nothing passes between an emitting object and people's ears. For 6-year-old children, sounds "live" in objects even when we do not hear them, go to ears or anywhere else, and then return to their "home." By the age of 7, children start conceiving of sound as moving in straight lines in all directions. Finally, after age 11, sound is understood as a kind of "tapping" that resonates and spreads with the mediation of air (it can also be conceived of as air itself). For older subjects, studies conducted with novices and experts in physics have shown that some novices conceive of sound as made of a substance (Linder, 1993; Linder & Erickson, 1989; Maurines, 1992).

Our study falls within the general trend of research showing that knowledge is structured in a domain-specific way (Wellman & Gelman, 1992, 1997). Hirschfeld and Gelman (1994) defined a domain as "a body of knowledge that identifies and interprets a class of phenomena assumed to share certain properties and to be of a distinct and general type" (p. 21). Biology, mind, physics, and number are the main domains studied. Naive representations that children build from their everyday experience are studied in order to find out if and how knowledge is organized, but different hypotheses have been advanced on these points. One of the main differences lies in the coherence attributed to this knowledge and in the nature of the hypothesized conceptual change. Three of these hypotheses which are particularly relevant to the study of knowledge in the domain of physics, are presented briefly below: ontological categories, naive theories, and knowledge in pieces.

The first emphasizes the role played by ontological categories, i.e., fundamental categories through which different forms of existence would be grasped directly (Chi, 1992; Keil, 1989). According to Chi, Slotta, and Leeuw (1994), entities in the world belong to ontological categories such as matter, processes and mental states. Each of these primary categories is seen as the root of a tree divided into several ontological subcategories. Misconceptions are attributed to a mismatch between the ontological category to which subjects assign a concept and the ontological category to which the concept usually belongs. In this framework, conceptual change occurs through the reassignment of a concept from one category to another. As such, it is assumed to be a rather sudden shift: "Once a concept has been re-represented on a different ontological tree, the concept immediately inherits the attributes of that tree. This immediate inheritance can provide the 'aha' phenomenon" (Chi, 1997, p. 230). In physics, people have trouble understanding concepts such as electrical current, heat, light, and force, because they assign these entities to the category of matter when in fact they belong to the ontological category of processes, more specifically to the subcategory of processes called "constraint-based-interaction" (CBI). The attributes of the constraint-based-interaction category are: no beginning or end, uniform in magnitude, simultaneous, multidirectional, non-causal, constraint satisfaction, and so forth. According to Chi (1992), it is more difficult to transfer a concept from one branch to another branch of the same ontological tree than from one ontological tree to another ontological tree, as is the case when an entity conceived of as matter has to be re-represented as a process.

The second hypothesis, which we see to Vosniadou (Vosniadou, 1992, 1994; Vosniadou & Ioannides, 1998) and to Carey (1985, 1991), is that naive knowledge is also organized, but within theories that are acquired in the course of development. The term "theory" is used to denote a relational, explanatory structure in which concepts are embedded and by which they are constrained. Vosniadou proposed two levels of depth in naive theories: framework versus specific theories. Naive framework theories are built early in infancy and are based on some fundamental ontological and epistemological presuppositions that define a domain (for example, the presuppositions of permanence, solidity, continuity, and so forth for the domain of matter). Specific theories are built from everyday experiences or instruction to explain a limited range of phenomena (for example, the shape of the earth). They are based on beliefs that give rise to mental models, under the constraints or presuppositions of the framework theory. The distinction between these two levels of depth in theories allows us to explain why some conceptual changes are more difficult than others. Beliefs are presumably easier to revise than the presuppositions entrenched in a framework theory. In addition to the construct of naive theory, Vosniadou (1992, 1994) borrows the construct of mental model from Gentner and Stevens (1983) and Johnson-Laird (1983). She considers that a theory is based on a few abstract and stable core presuppositions or beliefs, but that a mental model is a transient and analogical construction, elaborated on the spot for the purposes of solving a given problem. When an initial mental model is invalidated, either by everyday experience or by socially-transmitted knowledge, different kinds of conceptual change are possible. The less radical change consists in building a synthetic mental model that integrates new knowledge in a way compatible with the constraints of the framework theory. The more radical and more difficult change consists in revising the presuppositions of the framework theory.

According to Vosniadou, the presuppositions embedded in naive theories are tacit, but given that they constrain mental models, they can be inferred from them.

In their study on children's representations of the shape of the earth, for example, Vosniadou and Brewer (1992) inferred from the mental models children develop about the shape of the earth that these models are constrained by two presuppositions which are part of a more general naive theory of physics: (1) the ground is flat, and (2) unsupported things fall. The initial model built within these constraints is that of a flat earth (rectangular). When children learn the culturally accepted model of a spherical earth, they try first to build synthetic mental models that fit this new knowledge with the constraints of the two presuppositions mentioned above. This leads some children to believe that the earth is spherical but that people live on a flat ground, deep inside this hollow sphere, as in an aquarium. A real understanding of the way that people can live on a sphere without falling needs a more radical process of conceptual change in which the core presuppositions of the framework theory are themselves revised.

Carey's (1985, 1991) conception of naive theories is close to Vosniadou's. Conceptual change occurs in the course of development and can take on different forms: conceptual differentiation, conceptual co-alescence, change of type (reanalysis of properties and relations), or change in the core principles of a concept. Studies of children's conceptions of matter have demonstrated such conceptual changes in the period between 4 and 12 years. For example, children do not at first differentiate the concepts of weight and density or the concepts of air and nothing. Later they must reconceptualize material objects in order to construct a model of matter as continuous and homogenous (Carey, 1991; Carey & Spelke, 1994).

The third hypothesis by diSessa (1993) takes the opposing view. He argues that novice learners' knowledge of physical phenomena is not a logically organized structure that can be seen as a theory, but is more like knowledge in pieces. These pieces are p-prims (phenomenological primitives), i.e., shallow, self-explanatory interpretations of physical reality. They are phenomenological in the sense that they are responses to experienced and observed phenomena. They are specifically linked to these phenomena rather than being general or abstract, and their retrieval is thus mainly guided by surface features. They are primitive in the sense that they are self-evident to their holders and therefore require no further explanation. An example of a p-prim is people's explanation of the fact that a vacuum cleaner's motor speeds up when the end of the tube is covered. People attribute this phenomenon to the effort required from the motor to overcome the resistance generated by covering the end, whereas in reality, motor speeds up because there is less work to do because of decreased air resistance when the end is covered. This naïve explanation could be considered as a p-prim because it is not interconnected into a coherent structure with more general explanatory principles but it is related to the context experienced by people. In this example, the context is the effort people have experienced in their everyday life, when reacting to a resistance. Conceptual change is seen here as conceived as a reorganization that increases the internal coherence of p-prims. Because naive knowledge is considered to be made up of unrelated pieces, without naive theories or ontological categories structuring them through core principles or ontological constraints, there is no need to revise such general principles. Moving from intuitive knowledge to expertise requires developing, refining, differentiating p-prims, and above all, subordinating them to the formal principles of physics. According to diSessa, this process of conceptual change is primarily the result of instruction.

2. The present study

The purpose of the study reported here is to shed light on two of the points of disagreement between the different theoretical conceptions summarized above. The first point pertains to the degree of organization or coherence of naive knowledge; the second concerns the mechanisms of conceptual change. These two points were explored here in naive representations of sound by children between the ages of 6 and 10 years old, a period when the scientific explanation of sound has not yet been taught in school.

The first objective is to determine whether naive knowledge that children have about sound is fragmented and unorganized, as diSessa (1993) contended, or structured around core principles, either in the framework of ontological categories, as proposed by Chi et al. (1994) and Keil (1989), or in the framework of naive theories, as argued by Carey (1991) and Vosniadou (1994). If, as suggested by Chi et al. (1994) and demonstrated by Slotta, Chi, and Joran (1995), children and novices first assign physical processes to the ontological category of matter, they should begin by attributing the properties of objects to sounds. So, one way to find out if children's knowledge of sound is organized around some core principles is to see if they coherently attribute to sounds the properties of one or the other ontological category, matter or processes. The object properties considered in this study were substantiality, weight, and permanence. To study the properties ascribed to processes, we looked into whether the children had an idea about the vibratory process responsible for the production and transmission of sounds, and whether they thought that a medium was necessary for transmission. We also examined the children's representations of a sound's trajectory to see if it was sequential or simultaneous, with sound going either only to people or going everywhere. Knowledge coherence across properties was examined by determining whether children jointly attribute to sound the different properties of matter or the different properties of processes.

Our second objective is to investigate the mechanisms of conceptual change. If naive knowledge about sound is organized in terms of ontological categories, the concept of sound should first be assimilated by children into the ontological category of matter, as assumed by Chi et al. (1994), before being assigned to the ontological category of processes. In this view, sound will possess all the attributes of the category to which it is assigned. In other words, if children assign sound to the ontological category of matter, then they should assign all the attributes of matter to sound. Similarly, if they assign sound to the ontological category of processes, then they should assign it all the attributes of processes. If conceptual change is really a reassignment of sound from the "matter" category to the "process" category, the shift should be relatively direct and sudden. If, on the other hand, knowledge is organized into naive theories, it should be coherent inside a domain, and as assumed by Vosniadou (1992, 1994), the source of that coherence should be found in the explanatory core presuppositions underlying the mental models that children build in order to answer questions. In this case, conceptual change should be rather slow and gradual, and one should observe the coexistence of misconceptions and of culturally-transmitted scientific knowledge, at least for some developmental periods.

3. Method

3.1. Participants

The participants were 89 children: 29 preschoolers (mean age 6 years, range 5;4–6;4, 16 females and 13 males), 30 second graders (mean age 7 years 10 months, range 6;8–8;4, 14 females and 16 males), and 30 fourth graders (mean age 10 years, range 8;9–11, 14 females and 16 males). All of these children were attending a kindergarten or elementary school in Paris. They came from middle-class backgrounds.

3.2. Procedure

The children were questioned individually for approximately 30 min, using a semi-structured interview. They had to predict the outcome of experiments, justify their predictions, observe the outcomes, and explain the results observed. In other items, they had to judge productions of other children and to complete drawings. Their answers were recorded. For all children, the situations were presented in the following order: substantiality, trajectory, permanence, and weight. This order was selected in order to provide a logical progression of questions. For example, children had to think about how a sound is transmitted before thinking about its trajectory, permanence, or weight. Before being questioned, the children were told that they would conduct experiments and make observations with objects that make noise and sound (these two terms were used interchangeably during the interview).

3.3. Materials

3.3.1. Situation 1: substantiality[2]

Substantiality refers to the fact that sound is assumed to be made of matter and thus cannot pass through solids. The experimenter told the children that they

[2] In order to shorten the paper, one part of the study, which dealt with consistency among items *within* the property of substantiality has been deleted. In this part of the study, two other items were

had probably already heard noise through walls at school or at home: "You have certainly already noticed that we can hear some noises through walls, for example, at school or at home, your upstairs or downstairs neighbors. Could you explain to me why we can hear the noise?"

3.3.2. Situation 2: trajectory[3]

A noise was made with a small box that imitated a cow's mooing when it was turned over, and then a drawing (21 cm × 29.7 cm) depicting the box and three people all standing at the same distance from the box, was placed on the table by the experimenter. The children were asked to indicate on the drawing where the noise went, which path it took: "Look, this is an object that makes noise. You can try. Now I will show you a drawing on which you will draw where the noise goes, the path it takes."

3.3.3. Situation 3: permanence

A noise was made by hitting together two pieces of wood. When the noise was not heard any more, the experimenter showed the children a drawing depicting the room in which they were located. She asked them to draw where the sound went in the room, and especially how far. If the children answered that the sound went out of the room, then she showed them other drawings depicting the school, the street, the city, etc. and the children had to continue drawing where the sound went. "When I hit these two pieces of wood, we hear a noise. On this drawing showing the room we're in, draw what the noise does when I make it like this. Draw where the noise goes and especially how far it goes." The children were asked if sound goes on forever, or if it stops and stays where it is, or if it disappears and ceases to exist.

3.3.4. Situation 4: weight

The children listened to the noise of a clock and then the experimenter asked the following question: "A child told me that the clock becomes a little bit lighter each time it makes noise. Do you think she is right or wrong? Why?"

included. In the first one, the experimenter asked the children to predict whether they could hear the noise of a clock if it were put inside of a metal box (prediction phase) and then, she enclosed really the clock in the box and asked children if they could hear the noise with the box near their ears (observation phase in which children heard the ticking noise through the box). In the second item, the same procedure was repeated with a cardboard box. The results to these items showed that the belief that sounds cannot pass through objects or can pass because there are holes was more frequent in the prediction phase of the boxes situations, but of comparable frequencies in the observation phase. This part of the study can be sent to readers who are interested in it.

[3] The study of the trajectory of sound included three other drawings aimed at finding out whether there was an effect of the presence or absence of people and of the number and location of those people on children's representation of the trajectory of sound: (1) the box with one person, (2) the box with three people at different distances from the box, (3) the box alone. The results showed no significant differences between the different drawings. This part of the study also can be sent to readers who are interested in it.

3.4. Scoring

After having analyzed the entire set of explanations given by the children for each question, we categorized the responses according to whether or not they attributed to sound a given property of matter. A child's answer to a given question was classified in only one category (the slight variations in the frequencies of children across tables is due to the few cases in which a response was lacking or impossible to assign to a category). Inter-rater reliability was assessed on a random sample of 30 interviews (10 from each grade). Agreement between the two independent judges was high (94%). The different scoring categories are presented in the results section.

4. Results

For each property examined (substantiality, trajectory, permanence, weight), the scoring categories will be given first, and then results for the effect of grade on children's explanations will be presented. The results concerning coherence across properties will be given after the results for each property.

4.1. Substantiality

4.1.1. Scoring categories

Four kinds of arguments were given as justifications for why we can or cannot hear noise.

4.1.1.1. Noise is enclosed or there are holes. The children explained that we cannot hear noise because it is enclosed, or they said we can hear noise because it goes through holes. These holes could be visible (space under a door, cracks, keyhole) or microscopic. Some examples are "Noises go through the door otherwise they are a bit squeezed, pushed away" (Oli., preschool) and "There are small holes under the doors. Noises don't go through if there are no doors, no windows. Otherwise, walls should have holes" (Cam., 2nd grade).

4.1.2. Properties of the materials (see footnote 2)

The children explained that we can or cannot hear noise depending on the properties of the materials, i.e., their hardness, their "strength." Some examples of children's explanations are "Metal, we can hear less than cardboard. Cardboard is lighter than metal. Metal is harder than cardboard. Sound can go through cardboard more than metal" (Amé., 2nd grade) and "Sound can be as strong as metal or a wall. Sometimes, you think the opposite but me, I believe that's it" (Amé., 2nd grade).

4.1.3. Sound is immaterial

The children referred to the immaterial characteristic of sound. They compared it to a ghost or mentioned its invisibility or that it was of a different nature than

Table 1
Substantiality: argument frequencies in the observation phase of the wall situation, by grade

	Preschool	Second grade	Fourth grade	Total
Sound goes in holes	19 (79%)	10 (37%)	7 (26%)	36 (46%)
Properties of material	0	8 (30%)	4 (15%)	12 (15%)
Immateriality	4 (17%)	5 (18%)	8 (29.5%)	17 (22%)
Resonance, vibration	1 (4%)	4 (15%)	8 (29.5%)	13 (17%)
Total	24 (100%)	27 (100%)	27 (100%)	78 (100%)

their own body. Here are two examples: "Sound can go through even if there are no holes because it is invisible, as a ghost" (Ann., 2nd grade) and "Sound, it is not like us, it can go through anything" (Art., preschool).

4.1.3.1. Resonance and vibration phenomena. The children used the terms "to resound" or "to vibrate" in a relevant and appropriate way to evoke sounds transmission, even if the scientific explanation was not known. An example is "They are vibrations. When it hits on something, it makes it vibrate, it transmits it and then, we hear them."

4.2. Results

The significant effect of grade can be observed in Table 1 ($\chi^2(6) = 22.02$, $P <$ .01). Explanations referring to holes prevailed among the preschool children. This type of explanations regressed and was outnumbered by explanations about the relative strengths of materials in the second grade. These two arguments were still present in fourth grade, but in this group, arguments pertaining to the immaterial nature of sound or the role of vibration began to emerge.

4.3. Trajectory

4.3.1. Scoring categories

Two things in particular were analyzed in the children's drawings. The first was whether they represented sound as (1) going only to people or (2) also going elsewhere. The second was whether they represented sound as having (1) a sequential trajectory along which the sound goes successively from one place to another, or (2) a simultaneous trajectory where sound goes simultaneously to different places. Two examples of drawings are given in Fig. 1.

4.4. Results

A clear developmental progress can be seen in Table 2 ($\chi^2(2) = 14.95$, $P <$ .001). Most fourth-grade children represented sound as going in all directions, whereas only one-third of the preschoolers had this kind of representation.

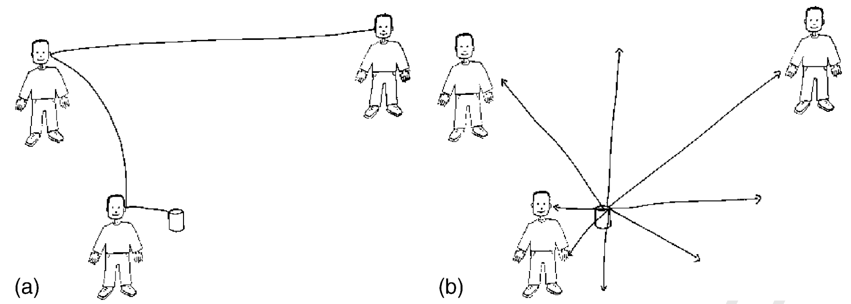

Fig. 1. Two examples of drawings: (a) sequential trajectory only to people; (b) simultaneous trajectory in all directions.

A sequential representation of the trajectory was rare. Only some preschoolers (five) and second graders (one) represented sound as going successively from one location to another.

4.4.1. Permanence

The question here was to determine whether children think that sounds, as objects, continue to exist when they are no longer perceived.

4.4.2. Scoring categories

4.4.2.1. Animism. Answers were classified as animism when the children told a story about sound as if it were alive, with intentions. This kind of response was observed only in preschool children. Here is an example: "It still exists but we don't know any more where it is. One day, it will not exist any more. All people have to die when they are too old" (Oli., preschool). Although we classified answers of this type as "animists," the exact status of these responses is open to discussion.

4.4.2.2. Permanence. Answers were classified in the permanence category when the children answered that sound would always exist. It was inferred that they assign permanence to sound, as in the following example: "It goes into the sky and it continues. It leaves with the air. It can go everywhere in the universe. It will always continue. It will always be with the air" (Ana., 2nd grade).

Table 2
Trajectory: frequencies of different drawings, by grade

	Preschool	Second grade	Fourth grade	Total
Only to people	17 (63%)	12 (40%)	4 (13%)	33 (38%)
To people and elsewhere	10 (37%)	18 (60%)	26 (87%)	54 (62%)
Total	27 (100%)	30 (100%)	30 (100%)	87 (100%)

4.4.2.3. No-permanence. Answers were classified in the no-permanence category when the children answered that sound disappeared, that it did not exist any more. Here are some examples: "At a moment, it doesn't exist any more because air stopped to vibrate and it became normal air" (Pie., 4th grade). To explain that sound disappears, children used terms such as to scatter, to evaporate, to wear out: "I don't think disappearing really exists because we have to leave some very small dust or a very small thing. Noise, it must be a little like air. It has to leave to go to another place. Maybe it can leave like that, I don't know where. It is different from when we were hearing it. One day, this different form will not exist any more. It will always exist a small thing that remains noise. It is matter that's not like air. Air, we feel when we go very fast and open the windows in a car. We feel air on our hands, not noise. We feel it but in another way. It is not a matter, whereas air is a matter which is felt" (Cyr, 4th grade). This example points out the ambiguity of the term "disappear." Sound can totally disappear but it can also be transformed, leave, hide, etc. This child clearly evoked the problem raised by the apparent disappearance of matter, which is seen as necessarily leaving something, even a very small bit of dust. This example is also interesting as far as the nature of sound is concerned. This child thought that sound was not made of matter after all but he did not yet know what it was. He compared it to air, saying that it was different, that we feel it but in another way.

4.5. Results

For the preschool children, it is difficult to draw any conclusions about the attribution of permanence because of the "animist" responses. Most of the second and fourth graders did not assign permanence to sound. A developmental trend was observed between preschool children and the others (Table 3) ($\chi^2(2) = 17.71$, $P = .0001$, with "animism" and permanence responses pooled).

4.5.1. Weight

Did the children think that sounds, as objects, have weight? Again, this question was explored in a situation in which the experimenter produced a sound with a clock and then said that some children believe that objects become a little bit lighter after emitting a sound. The child was asked if he/she agreed with this opinion and why.

Table 3
Permanence: frequency of subjects who attributed or did not attribute the property to sound, by grade

	Preschool	Second grade	Fourth grade	Total
Animism	11 (38%)	0	0	11 (12%)
Permanence	7 (24%)	7 (23%)	4 (13%)	18 (20%)
No-permanence	11 (38%)	23 (77%)	26 (87%)	60 (68%)
Total	29 (100%)	30 (100%)	30 (100%)	89 (100%)

4.6. *Scoring categories*

Children's responses were attributed to one of two response categories depending on whether or not they assigned sound the property of weight.

4.6.1. *Weight*

In weight responses, to justify why they thought that objects become lighter when they emitted sounds, the children gave various explanations: sound can leave and come back into the object, objects wear out or lose small particles, objects lose weight when sound is intense but not when it is weak, and so on.

4.6.2. *No-weight*

In no-weight responses, to justify why they thought that objects did not become lighter, the children said that sound has no weight, or that there is always the same thing inside the object, otherwise it would become soft, light. Some children said that sound was nothing but air. Other children said that the weight of sound was insignificant.

4.7. *Results*

Few children (16%) attributed the property of weight to sound. Table 4 shows that preschool children were more inclined to assign the property of weight to sound than were second and fourth graders. This developmental difference was significant ($\chi^2(2) = 6.63$, $P < .05$).

4.7.1. *Coherence among the different properties attributed to sound*

In Table 5, the substantiality category includes explanations about the presence of holes, and the relative strength of sound and of the material considered. The no-substantiality category includes explanations about immateriality, vibration, and resonance. For permanence and only for preschool children, animist responses were included in the permanence category.

Variability across children decreased with development. In the fourth grade, 50% of the children did not attribute any of matter's property to sound. None of the children attributed all three properties. In second grade, the two predominant patterns were the one that attributes only substantiality to sound and the one that

Table 4
Weight: frequency of subjects who attributed or did not attribute the property to sound, by grade

	Preschool	Second grade	Fourth grade	Total
Weight	8 (29%)	5 (17%)	1 (3%)	14 (16%)
No-weight	20 (71%)	24 (83%)	28 (97%)	72 (84%)
Total	28 (100%)	29 (100%)	29 (100%)	86 (100%)

Table 5
Attribution of the properties of matter: frequency of the different patterns of attribution, by grade

	Preschool	Second grade	Fourth grade	Total
Substantiality–permanence–weight	3 (13%)	1 (4%)	0	4 (5%)
Substantiality–permanence–no-weight	7 (30%)	5 (19%)	1 (4%)	13 (17%)
Substantiality–no-permanence–no-weight	5 (22%)	8 (31%)	9 (35%)	22 (30%)
No-substantiality–no-permanence–no-weight	2 (9%)	8 (31%)	13 (50%)	23 (31%)
Other patterns	6 (26%)	4 (15%)	3 (11%)	13 (17%)
Total	23 (100%)	26 (100%)	26 (100%)	75 (100%)

does not attribute any property of matter to sound. For the preschool children, 13% attributed all of the properties of matter to sound and only 9% did not attribute any. The most frequent pattern consisted of attributing substantiality and permanence to sound but not weight.

As Table 5 suggests, there was a strong hierarchical relationship between the three properties of matter attributed to sound. This relationship was quantified using a hierarchy index (HI) that compares the observed and expected errors based on a Guttman scale.[4] This index was found to increase with development (HI = .48 in preschool, .69 in grade 2, and .77 in grade 4). In other words, when the children attributed the property of weight to sound, they also attributed permanence and substantiality. Weight was the first property to be abandoned, then permanence, and finally substantiality.

5. Discussion

The goal of this study was to gather some empirical data on two points of disagreement between different views of conceptual development. The first point concerns the coherence of naive knowledge; the second concerns the mechanisms of conceptual change. The results on these two points will be summarized first and then discussed relative to the corresponding theoretical debates.

Four situations were designed to assess which properties children attribute to the phenomenon of sound. Four properties of the ontological category of matter were studied: solidity or substantiality, permanence, weight, and trajectory.

Concerning the observed coherence among the properties, we did not find two distinct groups of children, those who attribute all properties of matter to sound

[4] HI = 1 − (observed errors/expected errors). The number of observed errors was the number of patterns observed in the sample that violated the expected hierarchy between the items. The number of expected errors was the number of such errors that could be expected if the subjects in that sample had answered at random. This index varies from 0 when there are as many errors as expected at random, to 1 when the items constitute a perfect Guttman scale (no observed error). This index was been proposed by Longeot (1969).

and those who do not attribute any of those properties to sound. The different properties of matter seem to be attributed and abandoned in a hierarchical rather than synchronic way. Weight and permanence were the first properties to be abandoned. Substantiality seems to be most resistant and thus more central. Concerning weight, our results confirmed those obtained by Carey (1991): children less than 10 years old consider weight to be an accidental property of material entities. Consequently they can judge that an entity is material but does not have any weight.

The developmental results pointed in the same direction. They showed that during the age period ranging from 6 to 10 years, the various properties of matter studied here (permanence, weight, trajectory, and substantiality) are attributed to sound less and less often as age increases, but that substantiality seems to be part of children's representations for the longest time.

At first glance, the various forms of inconsistency underlined above seem to support diSessa's conception of naive knowledge. The variations could indeed be interpreted as an indication of knowledge in pieces, where different p-prims are activated according to the surface cues of the situation. An examination of the arguments used by children to justify their responses and the study of the developmental evolution of these arguments suggest another interpretation however. Relatively stable beliefs and presuppositions seem to underlie this apparent inconsistency. The observed variations in children's predictions are to a great extent due to the synthetic mental models that will be outlined below, by which children reconcile the constraints of the presupposition of substantiality (a solid cannot cross another solid) and everyday experiences showing that sound can pass through some solids. These synthetic mental models, in the sense used by Vosniadou, enable children to believe that sound can pass through a solid if this solid has holes, or if it is less strong, or less hard than sound. As a whole, the variations observed in the children's responses and arguments thus appear to be generally generated by the same mental model, but the different answers given depend upon what the child supposes about the presence or absence of holes or about the relative hardness of each material considered.

Data showing a lack of consistency among the properties cannot be interpreted as corresponding to an absence of structure in naive knowledge. The fact that children do not attribute all the properties of the matter to sound or all the properties of processes in a synchronic way does not mean that naive knowledge is not structured. The existence of a rather strong hierarchical relationship between properties speaks rather for a structured evolution of children's representations, one in which the properties of matter cease to be attributed to sound in a fixed order. Our results concerning knowledge consistency are thus more compatible with conceptions which assume some structuring of naive knowledge, either by naive theories or by ontological categories, than with diSessa's approach that knowledge is in pieces.

The second purpose of this study was to examine two views of conceptual change, one proposing a process that reassigns a concept to a new category, the other suggesting a gradual process of revision of the presuppositions entrenched in naive theories.

From this point of view our results support partially Chi's interpretation of misconceptions, according to which novices frequently assign to the ontological category of matter, physical phenomena which in fact belong to the ontological category of processes, in particular to the ontological subcategory "constraint-based interactions." The results of this study on representations of sound between 6 and 10 years of age point in the same direction as those of the Slotta et al. (1995) study on the concepts of electricity, heat, and light in ninth grade students with no background in physics.

However, our results do not support other aspects of Chi's approach to conceptual change. The first reason is that the change that we observed does not seem as sudden and as complete as would be expected in the case of reassignment. Certain properties of matter, like weight and permanence, appear to be abandoned long before others like substantiality, which seems to persist quite some time. This conceptual change thus seems to be a very gradual process, in which the different presuppositions linked to an ontology have different degrees of resistance, depending of their centrality. The second reason is that in this change, the concept of sound does not pass directly from the matter category to the process category. To the extent that the developmental trend can be inferred from cross-sectional observations, children seem to acknowledge the immaterial character of sound before having understood that sound is produced by a process of vibration. Children acknowledge the existence of entities whose nature is different from that of physical objects, but they are only able to define this nature negatively: these entities do not have the properties of physical objects. Thus, children explain that sound is something different from themselves, something transparent and invisible that can pass through walls as ghosts do. This suggests that perturbations, i.e., observations at odds with core beliefs, lead children to abandon or reformulate their beliefs rather than directly reassign the concept to another ontology. The picture of conceptual change in the case of sound seems thus to fit best with the idea that conceptual change occurs through the revision of beliefs entrenched in a naive theory. This does not mean that a concept can never be reassigned abruptly in another ontological category, but such a reassignment probably requires that the new ontological category exist beforehand. It is doubtful that the constraint-based-interaction category already exists at the age studied here. It is even doubtful that children can form this ontological category without formal instruction in physics.

The theoretical framework proposed by Vosniadou thus seems appropriate to account for the evolution of the concept of sound in the period of age covered by this study. The following description of this evolution will focus mainly on the attribute of substantiality, both because this property appears to be maintained the longest and because it is the property for which we conducted the most detailed analyses. The different categories of explanations given by the children suggest five mental models, from which two or three naive theories can be inferred.

The initial mental model seems to be a representation in which sound has the attribute of substantiality and thus cannot pass through other solids. This initial model (Model 1) was only observed in some children during the prediction phase (see footnote 1). As soon as the child has to explain observations that, at first glance, are contradictory with this model (for example, the fact that sounds can be heard through some solids), one or the other of two synthetic mental models is built that preserve the core presupposition of substantiality. The first one (Model 2) assumes that there are holes in solids, even when the holes are not visible, so that sounds can pass through. It is likely that the everyday experience children have with sand or water or anything passing through their fingers or through sieves underlies such analogical models. The second synthetic mental model (Model 3) assumes that a material object, here a sound, can pass through another solid if it is harder or stronger. It is likely, here also, that everyday experiences such as seeing a ball passing through a window pane or a pencil piercing a sheet of paper are possible sources of this analogy. This other synthetic model (Model 3) therefore makes an acceptable compromise between the observation that sounds can be heard through solids and the core presupposition of substantiality. The next mental model (Model 4) does not seem to be neither constrained by the presupposition of substantiality or by presuppositions about the ontological category of processes. It assumes that sound is transparent, invisible, and different in nature from objects and human beings. Some children refer to air, others refer to imaginary entities evoked in stories, such as ghosts, that have the power to pass through walls. The last mental model observed in this study (Model 5) is formulated in terms that are specific to sound transmission, such as vibrating or resonating. When they have to explain these terms, some children (but not all) describe a sequential process in which sound is transmitted by adjacency e.g., “When it hits something, it makes it vibrate, it transmits it, and then we hear it.” The distribution of these five mental models across the different school grades suggests that they are developmentally ordered. But one must keep in mind that this developmental trend was inferred from cross-sectional observations and needs to be verified in a longitudinal study.

What are the naive theories that constrain these mental models? The first three models seem to be constrained by the presuppositions underlying the framework theory of matter (permanence, continuity, solidity, etc.), the beginnings of which are known to already be sketched in infants (Spelke, 1991). Mental models of sound would thus be constrained at this stage by the framework theory of matter. However, in everyday experiences, sound does not behave exactly like other “objects” so some adjustments must be made. In the case of sound, the first phase of conceptual change does not seem to involve the revision of the initial presuppositions but rather of the gradual giving up of those presuppositions. They remain valid, but gradually become reserved for true objects.

This change seems to occur at two levels affecting the naive theory specific to sound on the one hand, and mental models on the other. The theory specific to sound seems to evolve following the abandonment of certain presuppositions about sound (weight, permanence) while others (substantiality) probably more central for the concept, are retained. In parallel, the construction of synthetic mental models makes the facts compatible with whatever presuppositions are maintained (i.e., if the sound cross through another solid, it is because there are holes).

It is difficult to say whether the fourth mental model (sound as an immaterial entity) is a synthetic model that still lies in the framework of a naive theory of matter, or if it is the expression of a new naive theory (theory of immaterial entities). We are inclined to favour the first interpretation. Children who give this type of explanation have observed that certain material entities do not have all of the potential properties of matter. They say that air, for example, which they can feel with their hands when they are in a car, is invisible. Why, after all, couldn't some objects be invisible and also weight less, without substance . . . etc.? Socially-transmitted myths, like those concerning ghosts, can help them imagine such borderline cases. All things considered, it could be the ultimate stage of evolution of the first specific naive theory of sound, where sound retains nothing else of matter than its "essence," after having lost all its attributes . . .

The fifth and last mental model, in which children rely on terms such as resonance and vibration to explain the transmission of sound, may be the first model constrained by presuppositions rooted in a framework theory of processes. Nevertheless, these presuppositions are clearly not yet those of the ontological category "constraint-based-interaction." Chi (1997) considers that the ontological category of processes is subdivided into three subcategories, procedure, event, and CBI. The ontological attributes of procedures and events ("decomposable, having a beginning and an end, sequential or unidirectional, contingent or causal subevents, explicit goal, terminates," p. 224) are very different from those of the CBI category ("no beginning or end, uniform in magnitude, simultaneous, multidirectional, non-causal, etc.").

According to Chi, one of the explanations of the difficulty that children have in understanding CBI processes is that, at the level of the surface's cues, they have some of the attributes of events (e.g., a beginning and an end, a sequential and causal aspect), whereas the comprehension of a CBI phenomenon is possible only by taking into account interactions at the molecular level, which do not obey these constraints but obey those of CBI processes. In other words, the revision of the naive theory of sound which seems to start at around the age of 10, and attributes to sound some of the properties of processes, is not the final step, at least for those who hope to understand scientific models of sound transmission.

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