PHYSICAL REVIEW SPECIAL TOPICS - PHYSICS EDUCATION RESEARCH **6**, 020114 (2010)

Identifying students' mental models of sound propagation: The role of conceptual blending in understanding conceptual change

Zdeslav Hrepic
Columbus State University, 4225 University Avenue, Columbus, Georgia 31907, USA

Dean A. Zollman and N. Sanjay Rebello
Kansas State University, 116 Cardwell Hall, Manhattan, Kansas 66506, USA

(Received 24 January 2010; published 24 September 2010)

We investigated introductory physics students' mental models of sound propagation. We used a phenomenographic method to analyze the data in the study. In addition to the scientifically accepted Wave model, students used the "Entity" model to describe the propagation of sound. In this latter model sound is a self-standing entity, different from the medium through which it propagates. All other observed alternative models contain elements of both Entity and Wave models, but at the same time are distinct from each of the constituent models. We called these models "hybrid" or "blend" models. We discuss how students use these models in various contexts before and after instruction and how our findings contribute to the understanding of conceptual change. Implications of our findings for teaching are summarized.

DOI: 10.1103/PhysRevSTPER.6.020114 PACS number(s): 01.40.Fk, 01.40.Ha

I. INTRODUCTION

To effectively reshape students' initial knowledge into scientifically accepted understanding, it is necessary to identify and address their existing knowledge. According to different theories of conceptual change, during the teaching process we may want to replace existing spontaneous reasoning, reorganize it, or refine and build on it [1]. Among many different types of students' difficulties, of special interest for physics education are those which originate from some structured cognitive concept or mental model [2].

Agreement does not exist about the exact definition of the mental model [3], but in general, the term refers to the internal representations that people form of the environment through their interaction with it. Our use of the term is consistent with Greca and Moreira: "A mental model is an internal representation, which acts out as a structural analogue of situations or processes. Its role is to account for the individuals' reasoning both when they try to understand discourse and when they try to explain and predict the physical world behavior" [[4], p. 116]. Mental models may contain contradictory elements [5] and are generally different from scientific models, which are accepted as valid if they are coherent, stable, and experimentally validated.

We perceive a mental model as a mental structure built of more fundamental cognitive and knowledge elements, e.g., p-prims [6,7] or conceptual resources [8,9]. To form a mental model, these elements must be assembled in a coherent way. In this case they become model features or aspects [10]. In the case of sound propagation, which is the topic of this paper, these model features are simply the properties of sound or the qualities that students attribute to sound.

After identifying mental models as such while using Greca and Moreira's definition [4] of a mental model, we have performed an additional validity check related to the nature of identified cognitive elements. For this purpose we used diSessa's [11] definition of mental models because to our knowledge, it imposes the most specific requirements on a mental model as a cognitive structure. According to diSessa "mental models should (1) involve a strong well developed "substrate" knowledge system, such as spatial reasoning, (2) allow explicit hypothetical reasoning, and (3) involve only a small, well defined class of causal inferences" [[11], pp. 53–4]. To illustrate this, diSessa wrote in personal communication: "My definition of mental model entails (1) strong "base descriptive vocabulary"–e.g., spatial configuration of identifiable kinds of things; (2) localized causality–i.e., just a few principles (e.g., "gears work by conveying motion via contact" or "resistors work by Ohm's law;" (3) explicit hypothetical reasoning (e.g., 'if this gear moves that way then connected gears move…')" [12]. Summarized, diSessa's requirements on mental models are (a) spatial configuration of identifiable kinds of things, (b) (few) principles of how the system works, and (c) (certain) predictive power.

II. WHY SOUND?

Although sound is an everyday phenomenon that we constantly observe, it is an area in which students display numerous difficulties in understanding [13–27]. Also, because sound is a wave phenomenon, its understanding may contribute significantly to understanding of both classical and modern physics.

Several studies [15–24,26,27] suggest that a naïve mental model is associated with sound propagation according to which sound travels as a particlelike object. These authors generally refer to this naïve model as a "particle model" of sound propagation. Wittmann *et al.* [27] also reported "particle pulses model" where students seem to describe the translational motion of particles traveling in successive pulses.

Within the topical area of sound, we concentrated on its propagation because previous research indicates that particle-based naïve model of sound propagation underlies a range of common alternative conceptions found among students at all educational levels.

III. CONTEXT DEPENDENCE OF MENTAL MODELS

Students' mental models may depend on context (e.g., [23,27–29]). In another words a learner may use several different, yet stable and coherent explanatory schemes [30] when explaining phenomena in the same concept area but presented in different contextual settings. Using Bao's [29,31] terminology, these students are in a mixed model state.

In order to investigate context dependency of students' reasoning, it is necessary to define context boundary. An important question is when do two situations become different enough to be considered different contexts? In the literature, problem situations are generally considered different contexts if they are approached differently by a nonexpert, while treated equivalently by an expert. This notion lacks specificity because it involves a circular relationship between context dependence and context definition thus creating virtually all nonexpert solutions context dependent. To avoid this ambiguity, for the purpose of this study we define two contexts as different if one situation cannot be transformed into another by merely changing the value of a contextual variable by a nonzero amount. Rather, the variable has to be eliminated (equal zero) or the difference between situations has to be described conceptually or verbally. Accordingly, situations differently represented to students (pictorially or otherwise) were also considered different contexts.

IV. RESEARCH QUESTIONS AND CONTEXT

This study attempted to answer following questions:

(i) What mental models of sound propagation do students use?

(ii) Do students' mental models change with context? If so, how?

Context of the study

Our research was conducted through individual interviews of students enrolled in The Physical World, a concept-based introductory physics course at Kansas State University. We considered several different levels of introductory physics classes as options for this investigation (concept-based, algebra-based, and calculus-based classes). For this phenomenographic study we preferred the concept-based course, as its students were less likely to be exposed to previous formal instruction about sound than students of other course levels. The conceptual level class was therefore more suitable for probing the students' initial (spontaneous) understanding of sound propagation.

The chosen concept-based class was taught in a large-enrollment lecture format. Students in this class typically major in wide variety of nonscience fields. An optional laboratory is associated with the course, but it does not involve experiments related to sound. The class used *Conceptual Physics, Eighth Edition* [32] as a textbook. Between the pre- and postinstruction interviews the class studied the following topics:

(1) Vibrations and Waves: Speed, Transverse, and Longitudinal Waves;

(2) Interference, Standing Waves, Doppler Effect;

(3) Sound: Origin, Nature, Transmission, Speed;

(4) Standing Waves, Resonance, Interference;

V. METHODS

Participants in this study were student volunteers enrolled in a concept-based physics course who accepted extra credit worth 2% of their total grade for participation. The interviews were conducted during Fall semester of 2001 and the total enrolment in the course from which participants were recruited in was $N=153$. All students who volunteered were included either in this study or the follow-up research [33].

The sample was sizable for phenomenographic study and consisted of 16 students who were interviewed about sound propagation before and after instruction. Another six students enrolled in the same class were interviewed only after instruction and one student only before (the student could not come to postinstruction interview). Thus, in all a total of 39 interviews were conducted with 23 student participants. We refer to the sample of students that we interviewed both before and after instruction as the "main" sample and those whom we interviewed just once as the "additional" sample. Half of the students in the main sample had taken two semesters of physics in high school. The other half had no high school physics. Twelve students were female and four were male. These students did not receive any feedback after the first interview. On average, our interviewees scored marginally higher than the class mean on the class exam on vibrations, waves, and sound. Since the study was phenomenographic [34,35] we had no hypotheses in this stage of research.

Interview protocol

Students' mental models were investigated using a semistructured interview protocol within the following contexts:

Context 1, 1a: Propagation of human voice through air with follow-up questions related to impact of sound propagation on air particles (context 1) and related to a situation in vacuum (context 1a).

Context 2: Propagation of human voice and its impact on a dust particle in the air.

Context 3, 3a: Propagation of a constant tone (context 3) and a rhythmic, beating tone (context 3a) from a loudspeaker and the impact of these sounds on a dust particle in the air.

Context 4, 4a: Propagation of human voice through a wall at macroscopic (context 4) and microscopic (context 4a) levels and its impact on wall particles.

Context 5, 5a: Students participated in an experiment with propagation of sound through a tight string with cans attached to its ends. We compared propagation of human voice through the tight string vs. air (context 5) and through the tight string vs. the loose string (context 5a).

All situations were represented pictorially (full protocol is given in Appendix A). During the interview, students had their own copy of the protocol with a drawing of the situation, a written initial explanation of the situation, and the initial question. Interviewees were encouraged to draw pictures while explaining their answers.

VI. DATA ANALYSIS

Science terms that have everyday meaning different from scientific meaning may present an obstacle for research investigating students' understanding of particular topics [36]. During the interview process we realized that while describing sound propagation, students frequently use the same terminology that experts do, but often with different meaning or without being able to explain the meaning. While describing sound, many students use a variety of statements commonly found in textbooks (e.g., "Sound waves travel through the air," "Sound is transmitted through the air," "Disturbance travels through the medium," "Vibrations move through the space."). However, these same students commonly make statements inconsistent with Mechanical Wave models (e.g., "sound propagates through the vacuum.").

For example, one can find the following statements in well known textbooks:

(i) "In this chapter we shall focus on sound waves that travel through the air and that are audible to the people."[[37], p. 426]

(ii) "Most *sounds* that we hear *are transmitted through the air*." [[32], p.344]

Correspondingly, a student with no high school physics was involved in the following exchange during the preinstruction interview:

> I: Does air play any role in this process of propagation of sound?
> JEWEL: I think air plays for the fact that the sound travels through the air and it isn't really doing anything else…it's just wave transmission to the listener's ear.

This comparison shows that this student, similar to many others, uses the same terminology that the experts do. Yet part of the student's statement that "the air…isn't really doing anything else [but being passed through by sound]" first indicated that the student's model is not a Wave model—the model surely held by textbook authors. The student's Non-Wave model was confirmed a few moments later when she stated that in a vacuum sound "echoes" better than in air as there is nothing to "absorb" it there.

Mental model identification

The observed language ambiguities in students' responses required additional care in data analysis. We determined students' mental models in two ways:

(1) Through a set of sound properties that were described by the students and could be uniquely associated with a particular model.

(2) Through the definitions that we constructed from students descriptions of sound propagation.

Students' statements that could be unambiguously associated with a model were purposefully restricted to a narrow set. For example, students attributed to sound a wide array of properties that were eligible as unique model identifiers for the particle or "entity" model. These included nearly all properties that Reiner *et al.* [38] list as "substance schema" i.e., properties common to material substances. The list includes descriptions of sound being containable (by something), corpuscular, gravity sensitive, inertial, pushable, frictional, and so on. Transcript examples are given in Appendix B for two of these properties (Corpuscular and Inertial). However, we restricted model identifying properties to only a few with the least possible room for ambiguity in interpretation. Consequently, although they are part of the "substance schema" list, none of the above mentioned properties was considered a unique identifier for the "Entity model." This approach substantiated the content validity of the results. We also made sure that model definitions come from students' statements and were not imposed on them. Also, the properties that students attributed to sound were in principle rather simple statements. For this reason they were relatively easy to classify unambiguously, so that the identified mental models were based on knowledge structures much simpler than the models themselves. This contributed to the reliability of the study. In order to probe whether students use the same or different models in various contexts, we identified the model only if the student stated everything that defines a model within the single context. In other words, we did not combine student's statements expressed in different contexts.

VII. FINDINGS

Using the above criteria, in addition to the scientifically accepted Wave model, we have identified what we called the "Entity" model as the dominant alternative model. Other models we have identified seem to be composed of different Wave and Entity model ingredients. These models we have called hybrid models. In this section we describe the identified models and their properties. We start with the Wave model and Entity model (most common incorrect model) i.e., two model components which appear to be the main building blocks for other described models.

A. Wave model

The Wave model that describes sound as a longitudinal, mechanical wave is the scientifically accepted model of sound propagation. Our operational definitions of the Wave model for interview data analysis were:

(a) Sound is a traveling disturbance of particles of the medium.

(b) Sound is a (longitudinal) vibration of particles of the medium.

Three of the 23 informants expressed the Wave model in three different contexts (1, 1a, 4a). Below we present two examples of the Wave model as expressed by students. The key for interpreting the statement of the first student is in the first and last sentence where the student unambiguously equates the sound wave with the specific motion of the air particles that he describes.

> ➢I: So what is sound wave?
> MR.T: Sound wave is um…nothing more than a motion, disturbance in the air, moving in one direction.
> I: OK. So what is disturbed?
> MR.T: The position of the particles…they don't move up and down, just this way back and forth.
> I: OK. So does air play a role in this propagation?

MR.T: Yes.
I: So what's the role of the air?
MR.T: The particles of the air, little molecules that make up the air make the…Through the motion they create the wave.I: Yeah, so just to recapitulate: What is physically going on when sound propagates?
JEWEL: (Pause)…sound is (laughs) movement of air particles back and forth until it reaches the listener, that's what the sound is.
I: OK. So sound is movement of air particles back and forth?
JEWEL: Uh huh (Yes).
I: OK. So when we create sound, what do we do?
JEWEL: We create a movement.
I: Of air particles?
JEWEL: Uh huh (Yes).

B. Entity model

According to students using the Entity model, sound is a self-standing unit different from the medium through which it propagates. Twelve of the 23 subjects expressed the Entity model in at least one interview. The model was observed in 5 different contexts (1a, 2, 3a, 4, 4a).

We have identified four sound properties that we uniquely associate with the Entity model. These are:

(1) Sound is independent–sound propagates through the vacuum, i.e., it does not need a medium, (2) Sound passes through the empty spaces between the medium particles (a property we called seeping), (3) Sound is a material unit of substance or has mass, and (4) Sound is propagation of sound particles that are different from medium particles. Examples of students' statements that describe the Entity model through each of these four properties are listed below.

(1) Sound is independent—sound propagates through the vacuum (does not need medium). Examples:

➢I: Would anything be different for sound in space with and without air?
ASHLEY: Um…I…don't think so…unless there are things in air that like the sound waves would come in contact with, that would like obstruct where they go, kind of. And then if there…I guess if there's no air then there is nothing for them, nothing to get in the way, so they travel, like, free of interference.
I: OK. So when would you expect sound to propagate kind of easier?
ASHLEY: Um, when there is like no objects in its way, when it's…just has free room to travel.
I: OK. So in case… when we have situation with air and without air…
ASHLEY: Uh Huh (Yes)
I: …when it propagates easier?
ASHLEY: Without air.
➢ DONNELIZER: I think that if there was no air in the room, it would just be…sound would come out louder to the person.
The student in the following example uses the term "wave" to denote the sound entity propagating through the vacuum.
➢ I: OK. And would anything be different for sound, in space with air and in space without air?
JORDAN: Without the air there would probably be no disturbance…to the wave itself. It'd just keep traveling probably.
I: OK. So it'd, how would it propagate with respect to situation with the air? Would it be easier, faster, louder, what would you say?
JORDAN: (Pause) I would probably just say last longer.
I: It'd last longer…
JORDAN: If it didn't kick any objects.
I: Uh huh (Yes).
JORDAN: If there is nothing there to interrupt the wave going it would just keep going.
I: OK. Now this thing, which keeps going; could you try to tell me what it is?
JORDAN: (Pause)…I just don't know how to…explain what…sound wave really is.

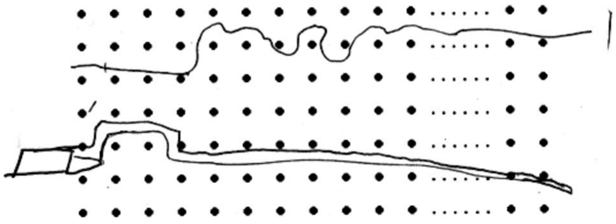

FIG. 1. A student's drawing of sound "working its way through" by "finding little open areas" in between the wall particles.

(2) Sound passes through empty spaces between the medium particles (seeping). Example:

➢ LORAIN: "As the sound moves, like as the sound comes through [the air] I think it might hit…Like it might find the spaces in between the particles [of the air] but, I think eventually it might also hit one. I mean it's not like it knows exactly where it's going."
➢ I: So sound comes from speaker's side. And what happens than at this microscopic level?
➢ DONNELIZER: It travels through just a little stuff. It just kind of works its way through, kind of like this (see Fig. 1.), finding any of the little open areas that it can, until it gets to the listener.
➢ VIRGINIA: …Well I would say that it's somewhat like a maze for the…for the sound. It just kind of works its way through until it gets to the other side. […] I don't think sound can move them [particles of the wall]. I think sound just moves around them.

(3) Sound is material—sound is a material unit of a "substance" different from the medium particles and/or has mass. In the two examples presented below, the conversation was made after each of those students at one point stated that the sound propagates through the vacuum:

➢ I: Does sound consist of anything material?
VIRGINIA: "Yes, I don't know of what, but yes, I am sure it does.
➢ I: So does air play a role in [the] process of propa-

gation of sound?
BIC: Ah, yeah it's, it's what carries it. […]
I: And is air different…I mean, this carrier, is it different from sound? […]
BIC: Oh, yeah, it would be different from sound. […]
I: So it seems like it's something different…in terms…as if it's…it's own entity, something kind of separated?
BIC: Yeah, it'd have to be some, it'd have to be something that it's gonna move the air. And so it's different one.
I: So how do you perceive this entity?
BIC: As noise. I mean is there anything that makes a noise or…?
I: I mean…is it something material, not material….
BIC: Oh…
I: …located, not located?
BIC: Material because it can be measured, you can measure how louder, softer how far it's traveled or something.
I: OK.
BIC: But just in this situation…
I: You can measure its mass?
BIC: Um, yeah. I would assume so…

(4) Sound is propagation of sound particles that are different from medium particles. Example:

➢ STAR: Well the, the air is what…the sound particles move through. And so in space they don't have any place to move through…
➢ MARK: But she can hear what's coming out of his mouth. So it's not that the air…the air doesn't actually move. It'll…just the particles will move through the air I guess.
I: What particles?
MARK: The um…like a…sound particles.

In addition to model identifying properties, we defined a list of properties inconsistent with Entity and Wave models. The sound property that we considered inconsistent with the Entity model is vibration of particles of and/or in the medium (around the same spot) that occurs as sound propagates. Properties inconsistent with the Wave model include (1) all Entity model identifying properties, (2) the property of "nonintrusiveness" (sound propagation does not affect the movement of particles in and/or of the medium), and (3) the property of "pushing or displacing particles" (sound moves particles of and/or in the medium in the direction of the sound propagation). We ensured that none of these inconsistent properties appear in the context in which we claimed that the model exists.

C. Blend models

A common feature of all models that we identified besides the Entity and Wave models is that they unify some characteristics of each of these models and form a new composite model. At the same time, by one or more features, these compound models are inconsistent with both the Entity and Wave models. We call this class of composite models blend models, or synonymously, hybrid models.

The first part of our definition of a blend model matches Vosniadou's [10] definition of what she calls "synthetic model." Synthetic models are "models which combine aspects of the [student's] initial model [one based on everyday experience] and the culturally accepted [scientific] model" [10].

In addition to this condition, we require that a blend model has a set of features that make it incompatible with the each of the two "parental" models. This means that each of these sets of features needs to be identified up front in order to identify a model as blend. In the case of sound propagation, parental models that compose blend models are the Entity model (students' common initial incorrect model) and the Wave model (scientific model). Parental models may or may not be the common initial and scientific model but this research and Vosniadou's [10] study indicate that that is what they typically are. Finally, Vosniadou considers usage of multiple models a form of a synthetic model. For this situation we adopt Bao's notion of mixed model state [29,31], which is also different in several ways from a blend model as will be explained later.

Greca and Moreira [4] use the term hybrid model for mental models that appear as a consequence of successive reformulations of students' initial model and they consider these models equivalent to synthetic models described by Vosniadou. At the same time this same construct has been known in cognitive science as a conceptual combination [39] and a conceptual blend [40]. Authors of this paper used the term hybrid model in earlier publications [26,41–43] because it etymologically describes this structure better. A Web search indicates that the term "hybrid" has also gained deep roots in a variety of different fields to denote the same type of construct or product. Across the science education research community, one can find examples of both terms—"hybrid" [44,45] and "blend" [46–48] when referring to this same type of concept construct. Taking all of these together, we propose that the terms hybrid mental model and blend metal model can be used synonymously and we consider them equivalent. For consistency in this paper, we will use the term blend model and its derivatives.

Below we list and describe three blend models associated with sound propagation that were expressed by more than one student in our study. These are:

1. Shaking model

According to the Shaking model, sound is a self-standing entity different from the medium but when it propagates through the medium it causes vibration of the particles of the medium (air particles, wall particles) and particles in the medium (dust particles). These particles of and/or in the medium vibrate on the spot. In addition to using this description i.e., definition for identification of the Shaking model, we also considered the following combination of the sound properties uniquely associated with the Shaking model: (1) Sound is intrusive—(particles of and/or in the medium) vibrate and (2) any sound property uniquely associated with the Entity model. The Shaking model was expressed by two students and in contexts 1, 1a, 4a). Example:

> ➢ JORDAN: I know that, like disturbance will come out from his [speaker's] mouth and cause the air, like…disturb it or… (pause)…it'll eventually reach the listener, and then he'll hear you.
> I: So how disturbance gets on the other side?
> JORDAN: Gets on to the listener?
> I: Yeah.
> JORDAN: Because it moves through the air.
> I: It moves through the air, so in the space without air would anything be different for sound?
> JORDAN: (Pause) Probably it'll, it wouldn't a…it wouldn't slow down, it'd just keep traveling.
> I: OK. Does propagation of sound affect the air?
> JORDAN: Um, yes.
> I: How?
> JORDAN: It sort of shakes up all the molecules in the air. So it shakes them up so they are moving as it passes through.
> I: OK. So this is impact of sound on air and impact of air on sound would be?
> JORDAN: It will be to change it and to weaken the disturbance eventually as it moves along.
> I: OK, so without air…?
> JORDAN: It'd just keep moving, without any change.
> I: OK, so would it go basically infinitely in that situation, totally without air?
> JORDAN: Uh huh (Yes).

2. Longitudinally Shaking model

The Longitudinally Shaking model is a special case of the shaking model as the type of vibration is here specified as the longitudinal vibration. In other words according to the Longitudinally Shaking model sound is a self-standing entity different from the medium. When it propagates through the medium it causes longitudinal vibration of the particles of the medium (air, wall particles) and particles in the medium (dust particles). These particles of and/or in the medium vibrate longitudinally on the spot. The model was expressed by three students and in contexts 1, 1a.

3. Propagating Air model

The Propagating Air model explains that sound propagates so that air particles travel from the source to the listener. We used this definition as the only identifying property for this model. It was expressed by two students and in contexts 4, 4a, 5, 5a. It appears that in our setting contexts 4 and 4a were triggers for this model. For that reason in Appendix D we give the example of this model in context 4a with the preceding discussion in context 4 to show the model as well as the contextual clue that triggered it in this instance.

Three other blend models were expressed by only one student each. We describe those three models below.

4. Vibrating Air model

According to the Vibrating Air model, sound is an entity different from the medium through which it propagates. The air molecules (as described by the student who put the model forth) constantly vibrate horizontally back and forth. This perpetual vibration of the air particles is identical with and without sound. When the source produces sound, this constant motion of air molecules transfers the sound forward. For the model description stated in student's words, please see Appendix C.

5. Ether model

In this model sound is propagation of the disturbance created by longitudinal vibration of etherlike particles that are different from particles of physical medium. These etheric particles may be called sound, sound waves, or sound particles. For details of the model stated in the student's words, please see Appendix C. The Ether model is the only model we identified according to our definition of a mental model, which did not satisfy all three of diSessa's criteria for a mental model as discussed in the introduction. Namely, the interview data gave generalities of proposed components of the system (as described) but they were not specific enough as a working mechanism that describes how the sound propagates. Therefore it did not satisfy diSessa's second criterion. The Ether model (as described in this single interview) also lacks the predictive power (diSessa's third criterion). All other identified models satisfied all three of diSessa's criteria.

6. Ether and Compression model

This model is a richly upgraded Ether model (the two models were expressed by two different students, both after instruction). It shares basic features with the Ether model but also has several additional features that give it more predictive power. The model is described below but due to the disproportional length, the transcript is not provided. In the Ether and Compression model, as in the Ether model, sound is propagation of the disturbance created by longitudinal vibrations of etherlike particles that are different from particles of any physical medium. During the interview these "etheric" particles were called sound, sound waves, or sound particles. Existence of these etheric particles and their vibration is not sufficient for propagation. Sound in order to propagate needs compressions and rarefactions of the physical medium through which it propagates. Compressions and rarefactions always exist in the medium regardless of sound propagation and sound itself has nothing to do with their formation. The air is always arranged so that it has some more or less dense spots, which then serve the purpose (of compressions and rarefactions) and transmit the sound. Solids that sound encounters (like the wall), serve as compressions—spots of higher density. Sound travels faster through compressions (than through rarefactions) thus propagating faster in solids than in gases. But compressions in air (gases) can move and fixed solid objects are static compressions. This explains why sound diminishes faster while traveling through static compressions (of solids like wall) than through moving compressions (of gases like air).

Although this model was expressed by only one student in our sample, there are several features associated with it that make it an interesting part of the discussion of our findings.

First, it is very complex and has very good explanatory power. In a very intricate way, the model explains why sound propagates faster though the solid wall than through the air and yet, it attenuates more while traveling through the wall. The student who described this model used it to explain sound propagation in six different contexts (1 through 4a). The model had an unresolved issue only in the last context when we compared propagation of sound through tight and loose string. Sound is heard better when the string is stretched and thus less compressed, at least horizontally between the speaker and the listener. When this fact was brought up, the student understood the problem with the model and although she could not resolve it, she did not want to (attempt to) change the model. Perhaps because it otherwise worked really well.

A further interesting point is that this model was expressed in a postinstruction interview and the student who expressed it had a perfect score (100%) on the class test related to this topic. In the test she outperformed even those participants in our study who expressed the Wave model. This indicates a need for attention because from an expert's point of view this model is incorrect so we later discuss further implications.

In the supplemental sample, we did not find anything significantly different from the main sample. The models found in the supplemental sample were a subset of those found in the main sample.

In a follow-up study we developed and validated an instrument that probes for the presence of mental models of sound propagation in student population on a large scale. Results of these findings will be reported in another paper.

D. Validation of identified cognitive structures as mental models

While talking about "identifiable kinds of things" diSessa did not restrict them to "correct" things and neither do we. We also do not restrict mental models to concrete "ingredients" (those that can be visualized) [49]. Rather, we recognize abstract "ingredients" as valid too, whether they are "correct abstracts" (like the electric field) or "incorrect abstracts" (like the Ether, an incorrect abstract concept that physicists developed themselves). We found that all identified models except the Ether model, also satisfy diSessa's [11] requirements. Therefore they involve [12]:

(1) Base descriptive vocabulary—spatial configuration of identifiable kinds of things (e.g., air particles, sound, sound particles, source, ether, medium, solid obstacle, etc.).

(2) Localized causality—a few principles of how the system works (e.g., longitudinal disturbance of particles of the medium; translational motion of sound, sound particles or air particles; continuous vibrational motion of sound particles, ether, etc.).

(3) Explicit hypothetical reasoning—certain predictive power (e.g., sound propagates through a vacuum faster than through the air because there is nothing to obstruct it there; sound travels through a solid obstacle because it needs particles to carry it and more particles carry it better than fewer particles).

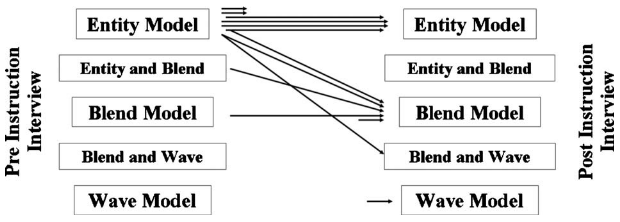

FIG. 2. The change in model states due to instruction.

The Ether model (as elaborated by the student who described it) is the exception as it fully satisfies only diSessa's first criteria. Still, features of the Ether model are a part of the Ether and Compression model and the latter one (again as described by the student) strongly satisfies all three of diSessa's criteria.

E. Pre-post-instruction model dynamics

We display students' model change between pre- and post-instruction interview using the representation shown in Fig. 2 which displays the model changes of all students in the main sample. The "Blend model" box in Fig. 2 stands for any of the observed blends, i.e., hybrid models. When multiple models were identified in the same interview, they were either a combination of Entity and some blend, or of a blend and Wave models. Each of these combinations is represented by a respective "box" in Fig. 2. Each arrow then indicates a single student's model transition. Long arrows represent students whose models were identified both before and after instruction. For some students a model was identified only in one of the interviews (represented by short arrows) and for three students a model was not identified either pre- or postinstruction.

Figure 2 shows there is a pattern in pre-post-instruction model dynamics. Students generally began with the Entity model and finished either with the same model or somewhere closer to the Wave model. In terms of pre-post-instruction model dynamics we have found no difference between students who did and did not have high school physics. The dominant initial and final models are virtually identical in both groups.

F. Use of multiple models

Students used multiple models simultaneously (i.e., they were in a mixed model state) in only two out of 39 interviews. This result may suggest that mental models of sound are not particularly context sensitive. However, we have listed below plausible alternatives to the aforementioned conclusion:

(i) The contexts were presented one after another and were all dealing with sound propagation. Thus, students may have perceived them as being more correlated than they would otherwise.

(ii) In order to probe for context dependence we identified a mental model only if all necessary statements were expressed within the single context and this also may have reduced the number of observed models.

VIII. DISCUSSION

A. Identified models and previous research

The particle model and the particle pulses model are alternative mental models of sound propagation described in earlier research reports. The model that we identified as the Entity model is in many ways analogous to the particle model. Linder [21] first used the term "entity" to describe students' notion of sound as being carried by individual medium molecules and passing from one molecule to another. In a similar way, the "sound particle" was earlier described as the materialization of the supply, a mixture of energy, intensity and speed, given by the source to the medium [18]. We could add to these descriptions that the sound entity, as we observed it, may or may not be material and it may or may not need the medium to propagate. Students may call this sound entity not only a sound particle but also a sound wave, a disturbance, or a vibration, all of which are scientifically acceptable terms.

Most frequently, students in our research claimed that the sound is a nonmaterial "entity," but in their responses it frequently interacted with the medium as if it were a material particle. In that sense it behaved as a photon does. An acoustical analog of a photon is a phonon. Therefore, one might suggest that the phonon is an appropriate name for the sound entity that we observed. However, this conclusion would imply that students actually understand this subject at a very high level of expertise, which is far from the truth.

We did not observe the particle pulses model that Wittmann *et al.* [16] identified in a case of the constant sound although we had the same contextual situation. This result may be due to different student levels in respective studies. Students in Wittmann *et al.*'s [16] study were engineering majors and at the time of the study they were taking their second semester of a calculus-based introductory college physics course. The reasoning found in our study that we perceive as being closest to the previously described particle pulses model would be that of a beating sound source (context 3a) which sends out successive pulses of sound entities in periods when it produces the sound and not in silent periods during pauses. Still, this mechanism does not seem identical to the particle pulses model of constant sound that Wittmann *et al.* [16] described.

Linder [21] and Wittmann [17] realized that some students understand a sound wave as propagating air. We described this understanding as the Propagating Air model, which is one of the blend models.

B. Sound entity

One of the features of the Entity model is that this "entity" is a highly abstract construct which supports Smith and diSessa's claim[50] that novices' intuitive reasoning has many abstract elements. Reiner *et al.* [38] showed that students' notions of a variety of natural phenomena are often extrapolations of our everyday experience with the mechanical world and visible substances. They developed a list of properties that describe matter called "substance schema" and showed that naïve notions of electricity, light, and heat are consistent with those properties. According to this schema, substances are pushable, frictional, containable, consumable, locational, transitional, stable, additive, inertial, gravity sensitive and can be of a corpuscular nature. Eshach and Schwartz [51] probed middle school student understanding of sound with respect to the "substance schema" and found that it does not seem to fit Reiner *et al.*'s [38] schema in all respects. In particular, they did not observe "stable," "corpuscular," and "inertial" properties. They also found that, according to students, sound can exert an internal inherent force upon itself that keeps it in motion. Finally they realized that in the case of sound students' idea of "additivity" is different than for the "regular" substances.

In our research we did observe students describing the three substance schema properties which were not observed in Eshach and Schwartz's [51] study (those properties with examples are listed in Appendix B). This may be because our sample was considerably larger and also because we were dealing with students at a tertiary level as opposed to middle school level students. However, like Eshach and Schwartz [51] we too see reasons for reconsidering substance schema properties in order to accommodate students' notion of sound. In addition to sound's problematic "additive" features, we see problems also with inconsistencies among different students. Namely, if accounts by different students are considered, sound may or may not be material or with mass. It also may or may not push the medium, be pushed by it or exhibit other substance schema properties. Finally, a student's own ideas about effect of the sound propagation on the particles of the medium may depend on the context. So the same student may state that sound pushes air particles but not wall particles. In conclusion, revisions of "substance schema" may be necessary in order to accommodate naïve notions of sound. However, it is clear that more research is needed on this topic.

C. Mental model dynamics

In this study students expressed only two "fundamental" models in the domain of sound propagation—a community consensus model (Wave) and the dominant alternative model (Ether). However, students showed a lot of inventiveness in fusing these two models into new blend models. This gives a new perspective to Marton's claim that when the learning of a particular physics topic is explored through systematic qualitative research, researchers are often able to identify a small finite set of commonly recognized models.

Our research, as well as Wittmann's *et al.* [16] study, shows that students' answers and models are context sensitive but in our data we also see evidence that students strive to be self-consistent in construction and usage of mental models and model features. Among the various theories of conceptual change proposed by previous researchers, our results seem to be in best accordance with Vosniadou's [10] theory of model upgrading through life experience and formal instruction. She has found an identical type of model fusing in her study of children's understanding of the shape of the Earth, as we did in the case of sound. In our study not only do models blend (hybridize) as whole but so do their features. For example, after the instruction, five students from our sample stated that particles of and/or in the medium will vibrate back and forth and *at the same time* also travel toward the listener. This statement was not found before the instruction.

Blend models can be extremely complex and very uniquely composed. The best example for this is the model we described earlier as the Ether and compression model. Therefore, we believe that another upshot of the concept of blend models is that that we will never be able to close the list of mental models related to a particular topic although the majority of students actually share only several models.

D. Mental model creation

In this study students rarely displayed coherent reasoning at the level of a structured model without being prompted with additional questions, especially in preinstruction interviews. For example, models were rarely found simply after the first general question about propagation of the speaker's voice. However, they were frequently found when additional model targeting questions in the context 1 and 1a were asked. Thus, some of these models may have been generated on the spot in the student's attempt to provide some rationale for the presented situations. So although sound is one of the most common of daily-life phenomena, students seem unlikely to form a mental model of the phenomenon unless they are requested to provide some explanation for it. This finding agrees with notion that people tend to avoid the "wasting" of mental energy [5,52]. We don't think about things unless we must for some reason.

E. Mental model context dependence: The issue of self-consistency

We find that using different explanations in different situations is generally an acceptable "technique" for students. However, they strive to construct more consistent and more parsimonious explanations if possible [52]. In an attempt to understand and explain a phenomenon, students strive to be self-consistent and to consolidate answers throughout the situations, which they perceive similar enough to do so. Our data supports this claim. In 12 instances students changed their previously given answer related to some of the earlier discussed contexts when their models seemed incongruent with a newly presented context. Of these 12, 11 were related to the effect of sound propagation on particles of and/or in the medium ("intrusiveness" of the sound). In each of these cases, when an answer was changed the new answer improved the overall self-consistency of the student's answers. For example a student who said in Context 1 that sound would not affect the air particles, thought in Context 3 that sound would affect the dust particle. Then, on her own, she decided to change her previous answer with respect to the air and stated that sound would move air particles as well. This finding agrees with Norman's claim that mental models are parsimonious—students prefer fewer explanations that can explain more situations. A 12th change of the previously given answer, one not related to sound intrusiveness, was neutral with respect to self-consistency.

If we take into account these coherency-increasing changes during interviews as well as previously described model-building and model-maintaining strategies that students employed—we see evidence that a number of students at this level do try to achieve global-coherent explanations (across situations). This was not the case with middle school students [51] who were satisfied with local-coherent explanations, i.e., by being self-consistent within a single situation.

Still, the features or aspects [10] of students' mental models were changing across the contexts frequently. As an example, there were four students who used the Entity model in air context as well as in wall context during the same interview. Three of these students stated that during sound propagation air particles are pushed away from the source but the motion of wall particles is unaffected. The fourth student stated the opposite. Yet the model was the same in all of these cases and respective contexts. In other words, because students assigned different interactive properties to sound in different contexts, they do not necessarily use different models.

Even though aspects of the model change notably across the contexts and much more than models do, this finding is still in agreement with our claim that students endeavor to be self-consistent. To illustrate this claim, consider a moving ball and its interaction with objects on its way. Although we may have in mind a very clear picture of ball propagation, its shape, mass, and velocity, our answers would be different if we are asked about the outcome of an interaction of this ball with a glass window, concrete wall, or a tree branch. In the same way, students may have exactly the same model, yet give very different answers when asked about dynamics of particles of and/or in the different mediums.

Another implication of this discussion is that although a situation in an interview setting may be different in this respect from a multiple-choice test, we would not say it is accurate to claim that students generate models randomly in different contexts [29,31]. At least they do not in the probabilistic sense of the term "random."

F. Model states

A student's mental model state [29,31] is defined by the mental model(s) that the student uses across different contexts. As a mental structure, a mental model is built of more fundamental cognitive and knowledge elements, which, when assembled into a mental model become its features [10].

Figure 3 depicts our perspective on various model states and their relationship with knowledge elements, i.e., model features. Students who use disconnected knowledge elements are in a "no model" state. Students in a "pure model" state construct a model by connecting features pertinent to this model and applying the model consistently across various instances. An "instance" in this study is equivalent to a context but in general it may also denote a question. Students in a "mixed model" state use two or more mental models. In each instance, they apply one of these models. Students in a "blend model" state construct a single model from features

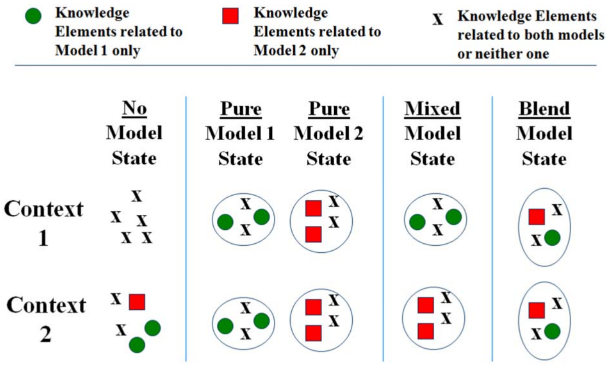

FIG. 3. (Color) Mental model states.

associated with different models. In a blend model state they apply respective blend models consistently across various instances. Thus, a blend model state (i.e., hybrid model state) is a special case of a pure model state. The need for this distinction stems from our interview data and as represented here gives a more structured perspective on previous results related to mixed and hybrid models (e.g., [10]). Also a possible development of the hybrid model state through instruction and the difficulty of detecting it with students have an important implication for teaching as we explain later in Sec. IX B.

Other physics areas, where student's transitional knowledge has been described in terms of blend models or blend knowledge, in addition to earth science [10] and sound [26,43], include Newtonian mechanics [43,53], electrostatics [54], optics [44], and electromagnetic waves [47,48].

IX. IMPLICATIONS FOR TEACHING

Two of the biggest obstacles to overcome while teaching sound are the language ambiguities in the domain of wave propagation and blend models that can completely escape the radar of common formative and summative testing methods. In this section we address these two issues and offer suggestions to overcome them in accord with our results and results of earlier research.

A. Language barriers in teaching of sound

We showed that language may be a significant barrier in effective communication related to sound. The reason is that many of the words that experts (and laymen alike) use while describing sound and waves in general are "borrowed" from historically developed vocabulary describing dynamics of visible substance. Language phrases that are used across different ontological categories may impede learning and create misconceptions [46]. This creates a particular problem in the teaching of sound because our and other [51] results show that students naïve conceptions about sound are in many aspects well aligned with the "substance schema" [38]. For these reasons, we caution carefulness in terminology selection when explaining sound propagation by choosing less substance-oriented language (such as propagate rather than travel, loudness rather than volume, and so on). We also suggest careful follow-up on the meaning of the terms used.

B. Blend models and the correctness of answers

Although it is certainly not a rule, this study shows that it is possible for student(s) with a blend model to have an even better test score than student(s) with the correct Wave model. Only one of all of the interviewed students had a perfect score (100%) on the test related to sound and vibrations. This was "Star"—a student who in the postinstruction interview used the blend model that we called the Ether and Compression model. Two students who expressed the Wave model in the postinstruction interview scored 80% and 65%, respectively. The test was in a multiple-choice format and addressed sound and vibrations, not specifically targeting the mechanism of sound propagation. However, of all the interviewed students, the two "Wave model students" had the two best scores on the extra credit portion of the test, which included some conceptual questions from our interview protocol. The conclusion is that, in the case of sound, a student does not necessarily need to have the correct Wave model for a perfect score. Conversely, earning a perfect score does not necessarily mean that the student has the scientifically accepted model.

C. Determining "common denominator" mental models for practical instructional use

While acknowledging subtle differences between models of every single student, we want to discuss commonalities between models of sound propagation observed in our study and previous research in order to make current findings operable for instructional use. Before addressing models as conceptual mechanisms of sound propagation, we want to bring up a specific understanding of what the sound is that may be associated with different models of propagation. This understanding is that the sound is what we hear, i.e., it is exclusively what we hear. This is a well known predicament and the dilemma of whether or not there would be a sound if a tree falls down in the middle of a forest where there is no one to hear it is well known and can be even found as a textbook "problem," e.g., [55]. The notion of the Ear-Born sound is not a model for a mechanism of the propagation but rather a definition of what the sound is and can be associated with more than one mechanisms of propagation. Another feature of the Ear-Born sound is that it is a partially correct idea and is well aligned with our daily definition of the sound. This makes it an important issue to keep in mind while teaching sound.

Models that we identified (as well as their variations or submodels) can be distinguished according to the answers that they give for the four questions below.

(1) What is sound?

(2) What happens to the sound without the medium?

(3) What are the dynamics of the particles of the medium during the sound propagation?

(4) How are these dynamics related to the sound propagation?

According to these criteria, four generic ("common denominator") models i.e., mechanisms of sound propagation can be distinguished as listed and summarized below. These four generic models can be viewed as four fundamental categories of student mental models of sound propagation.

➢ Wave model
➢ Independent Entity model
➢ Intrinsic model
➢ Dependent Entity model

We start a description of generic models with the Wave model and Independent Entity model as they represent the parental models involved in the blending of the remaining two generic models (Intrinsic and Dependent Entity).

1. Wave model

According to the Wave model: (1) Sound is a vibrational motion of particles of the medium caused by the source of sound. (2) Without the medium, sound can neither exist nor propagate. (3) When sound propagates, particles of the medium vibrate around the same point longitudinally (along the direction of sound propagation). Transversal and circular vibrations are (incorrect) Wave sub-models. (4) This particular motion of particles of the medium is the sound.

The model as described above corresponds to the "Wave model" that was identified earlier.

2. Independent Entity model

According to the Independent Entity model: (1) Sound or a sound particle is a self-standing entity different from the medium through which it propagates. Sound does not need the medium to propagate. It propagates independently through the empty spaces in between the medium particles. (2) Without the medium sound can exist and propagate. (3) Particles of the medium either (a) travel away from the source toward the listener, (b) vibrate around the same point or (c) do both (a) and (b). In one version of this model, the motion of the particles of the medium that occurs while sound propagates is caused by the sound entities as sound travels away from the source (the medium particles move this way because sound affects their motion). In another version of the Independent Entity model, the motion of the particles of the medium that occurs while sound propagates is not different from their motion without sound (i.e., sound entities in this case are not "intrusive" on particles of the medium, as we called this property).

The Independent Entity model as described above corresponds to "Entity," "Shaking," and "Longitudinally Shaking models" described before.

3. Intrinsic model

According to the Intrinsic model: (1) Sound is a translational motion of particles of the medium caused by the source of sound. (2) Without the medium sound cannot exist and cannot propagate. (3) When the sound propagates, particles of the medium travel away from the source in the direction of sound propagation. At the same time and in addition to this motion, particles of the medium may or may not vibrate. (4) This particular motion of particles of the medium away from the source toward the listener is intrinsically the sound.

The model as described above corresponds to "Propagating Air" identified earlier. Intrinsic model differs from the Wave model with respect to the dynamics of the particles of and/or in the medium. Unlike the Wave model, in the case of the Intrinsic model they undergo translational motion away from the listener. These two models have in common that particular motion of particles of the medium IS sound. At the same time, for both the Intrinsic model and the Independent Entitiy model, the translational motion of sound carrying an entity from the source to the listener represents the mechanism of sound propagation.

4. Dependent Entity model

According to the Dependent Entity model: (1) Sound is a self-standing (Independent) entity different from the medium through which it propagates. However, as in the case of the Wave model, in order to propagate sound needs the motion of the particles of the medium. Due to this motion of the medium particles, sound propagates through the empty spaces in between them. (2) Without the medium sound can exist but it cannot propagate. (3) When a source creates the sound, it also sets the particles of the medium into motion so they either (a) travel away from the source toward the listener, (b) vibrate around the same point, or (c) do both (a) and (b). In another version, particles of the medium move in a specific way (as defined individually by student) constantly and their motion is not affected by the sound propagation. (4) The motion of the particles of the medium enables the sound to travel through the empty spaces in between them.

The Dependent Entity model as described above corresponds to "Vibrating Air" and "Ether and Compression" models described before.

D. Why "common denominator" models?

The generic ("common denominator") models described above are in terms of observed students' model features comprehensive set of mental models of mechanism of sound propagation. They focus primarily on what sound is rather than on how particles of the medium move. Thus they target students' understanding of sound propagation at a more fundamental level. For instance, consider the notion of sound propagation accompanied by air particle motion from the speaker to the listener. From the perspective of sound definition, this mechanism can be associated with three different models: (1) Intrinsic model (this movement is the sound), (2) Dependent Entity model (sound is an entity that propagates due to this motion of the air particles), and (3) Independent Entity (sound is an entity different from the medium, it propagates with or without the medium but when it propagates through the medium it pushes the air particles this way). Finally, the above mentioned mechanism can be associated with the Ear-Born sound (this motion causes sound in the ear only). The same example applies to any vibrational (or combined translational and vibrational) dynamics of the particles of the medium as well. Therefore we suggest that eliciting and addressing students' understanding of sound propagation at the level of generic models is instructionally far more meaningful than at the level of the dynamics of particles of the medium.

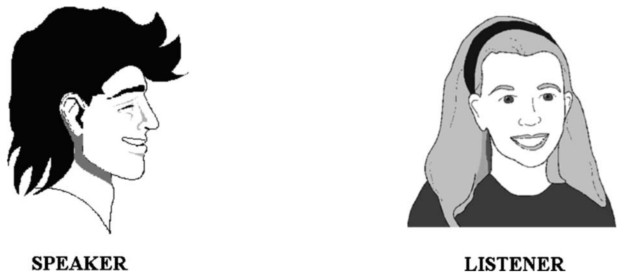

FIG. 4. Picture available to students for better understanding of the situation and for optional drawing during discussion related to context 1 in interview protocol.

X. POTENTIAL BIASES OF THE STUDY AND CORRESPONDING RESOLUTIONS

We describe below some potential biases that could have affected the study.

(1) The sample was not randomly selected. For this reason no conclusions can be made about statistical difference and its possible significance between the interviewed group of students and the class as a whole. However, finding the statistical difference and significance is never the aim in phenomenography. What we care about is a qualitative description of phenomenon under study. For our purpose it was significant that official quiz results related to the topic of vibrations and waves showed that our sample was not worse than the class average. They performed just slightly better than the class as a whole.

(2) Members of the sample were not randomly assigned to groups. Therefore, we cannot determine the exact impact of the preinstruction interview on the postinstruction interview although we had a group of students interviewed only after the instruction. Regardless, results obtained in interviews allowed for a logical speculation about the extent of the influence of the first interview on the second one. Generally we found that our interviewees kept in mind the postinstruction interview during the lecture but this did not impact their learning approach and postinterview answers in any systematic way. Also, as shown before, this did not result in overly correct postinstruction answers which could (although not necessarily) be an indication of a large impact of preinterview.

(3) The ratio of female to male students in the sample (2.3:1) was different than in the class population (1.2:1). According to Creswell [56] a sufficient number of subjects for this type of research is ten participants. Ideally these subjects would be five male and five female students, so this study involved more than an “optimal” number of students (five) within each of these groups (we had 16 females and seven males).

(4) Determining the model that a student used brings a bias to the classification. This was addressed so that standard reliability checks were conducted throughout the research.

XI. CONCLUSIONS

In this study we have identified eight different mental models of sound propagation. Although this number is relatively large, a simple pattern appears in their relationship. We have identified the Entity model, which is a dominant alternative model and also most often the “starting point model” in spontaneous reasoning about sound propagation. Another essential model is the Wave model, which is the community consensus model. All other models seem to be composites of these two main models as they combine some of the features of the Entity and Wave models. We have called this class of composite models blend models or hybrid models.

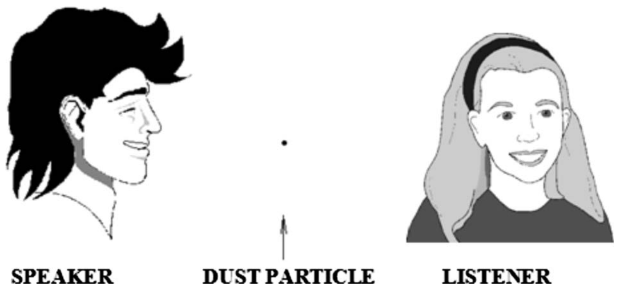

FIG. 5. Picture available to students for better understanding of the situation and for optional drawing during discussion related to context 2 in interview protocol.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. National Science Foundation under Grant No. REC-0087788.

APPENDIX A: STRUCTURE OF THE INTERVIEW PROTOCOL

1. CONTEXT 1. Voice-Ear

We have two people in the situation as in the picture below. As one of them talks, the other one hears him or her. Please try to describe as fully as possible how the sound propagates in this situation. Please feel free to draw on the picture (Fig. 4) as you are explaining.

Follow-up questions, depending on the answer:

➢ Does the air play any role in process of sound propagation? (What is the role of the air in process of sound propagation?)

➢ As the sound propagates, does it affect the air in any way? If so, how?

Context 1a:

➢ Would anything be different for sound in the space without air and in the space with air?

2. CONTEXT 2. Voice-dust particle

Now suppose we have a dust particle floating motionlessly in front of the silent speaker (see Figure 5). There is no wind in the room. Then the speaker starts to talk. If this dust particle was previously still, will the sound of the speaker’s voice have any influence on the dust particle?

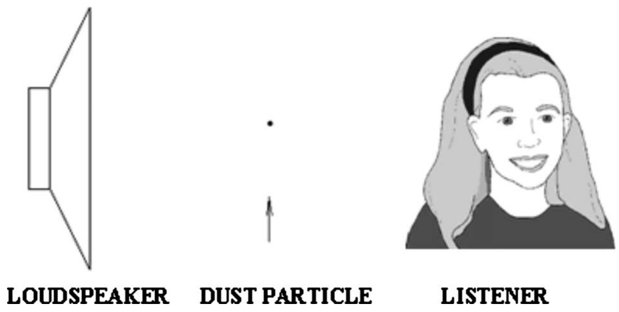

FIG. 6. Picture available to students for better understanding of the situation and for optional drawing during discussion related to contexts 3 and 3a in interview protocol.

3. CONTEXT 3 and 3a: Loudspeaker-dust particle

Let's consider now the following situation in which we have a loudspeaker instead of a human voice as the sound source. Now the dust particle is in front of the loudspeaker playing a single constant tone. Suppose at first moment the particle was motionless and then we turned the loudspeaker on. Do you expect that this sound would affect the dust particle?

Context 3a:

➢ Would anything be different in the motion of the dust particle if the loudspeaker (Fig. 6) will be playing slow rhythmic beats in on-off sequence? Like a very slow drum beating. (Would there be any difference with respect to continuity of movement of the dust particle for constant sound and slow beating sound?)

➢ Can the sound of a loudspeaker cause that dust particle to get closer to the loudspeaker than it was originally due to sound propagation?

4. CONTEXT 4 and 4a: Voice-obstacle-ear

Context 4: Now we have two people in two different rooms separated by a wall (Fig. 7). The wall is made of solid full bricks and the ceiling and the floor are made of concrete. What would you say about the possibility for these two people to hear each other's voice if they talk loudly and the wall is relatively thin?

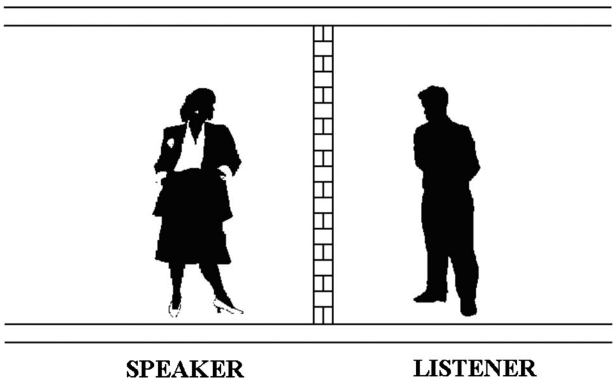

FIG. 7. Picture available to students for better understanding of the situation and for optional drawing during discussion related to context 4 in interview protocol.

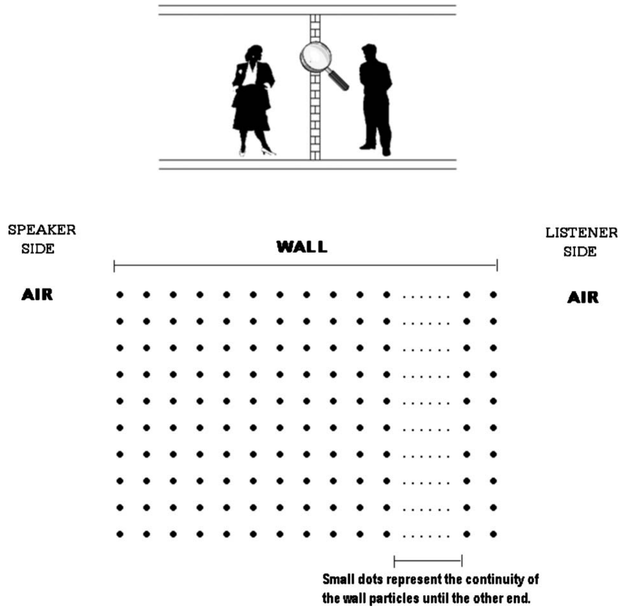

FIG. 8. Picture available to students for better understanding of the situation and for optional drawing during discussion related to context 4a in interview protocol.

If hearing is possible:

➢ How does the sound reach the listener on the other side in this situation?

➢ How does the thickness of the brick wall influence the loudness of the sound received by the listener in another room?

If hearing is not possible:

➢ Why?

Context 4a: Now let us suppose we have examined the microscopic structure of the wall and found out that the particles of which this wall consists are arranged as shown in the picture (Fig. 8) below.

➢ What happens on this microscopic level as the sound reaches the wall?

➢ Does the propagation of the sound affect the motion of the particles of the wall? If so, how?

➢ Why is sound quieter on the listener's side of the wall than on the speaker's side of the wall?

FIG. 9. Picture available to students for better understanding of the situation and for optional drawing during discussion related to context 5 in interview protocol.

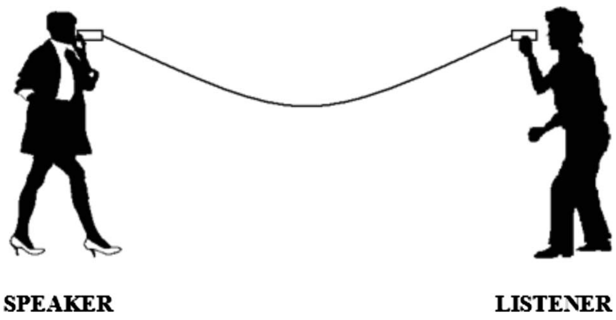

FIG. 10. Picture available to students for better understanding of the situation and for optional drawing during discussion related to context 5 in interview protocol.

5. CONTEXT 5 and 5a: Voice-two cans and string-ear

Context 5: Now each of us will hold one of these two cans that are connected with rope (approximately 10 m long) Figs. 9 and 10. I will go in another room as far as necessary to have this rope tighten between us and I will be in the position where we can see each other through the door. I will speak into the can on my side of the rope and you lean your ear on the opening of the can on your side. After that we will remove the cans and I will speak normally (without cans) so that you can compare how you hear me in these two cases.

Before the experiment with tight rope (context 5):

➢ Do you expect you will hear my voice better WITH or WITHOUT the cans in this setting if I speak equally loud? Explain why?

After the experiment with tight rope:

➢ Did you hear it better with or without these cans and rope?

➢ How do you explain that?

➢ How do you explain that this time we hear the sound better with some material between us and in the previous case the wall was diminishing the loudness of the received sound?

Context 5a:

Before the experiment with loosened rope (context 5a):

➢ If we repeat this experiment, would you expect to notice any difference in the loudness of the sound you receive if the rope is NOT tightened and if it IS tightened? Explain why?

After experiment 1 (with tight rope):

➢ Did you hear it better with tightened rope or with loosened rope?

➢ How do you explain that?

APPENDIX B: EXAMPLES OF ENTITY-LIKE SOUND PROPERTIES CONSISTENT WITH SUBSTANCE SCHEMA

Corpuscular–Sound has spatial volume, structure. Can be dissolved/broken into pieces.

> ➢I: OK. And why is it [sound] quieter on the other side [of the wall]?
> DONNELIZER: Because it has more to go through. The sound just kind of…it kind of …this with wall, this hard thing, it kind of breaks it up and it just loses a little piece. It just loses a little bit less sound as it gets through it. And so that's why it ends up not as strong. 'Cause it could be…I thought of it as of thickness, you know, like sound is this big [shows a wide area with hands] when the speaker talks and as it gets through it kind of gets broken up where by the time it gets here, you know right here, it might only be this big [shows a small area with hands].

FIG. 11. Student's drawing over provided template to illustrate the statement (Ashley).

Inertial–Sound tends not to change direction of propagation. String loses sound because of the curvature.

> ➢ ASHLEY: Um. I think it [sound] would be louder when the rope is tight [than loose], because they'd all be going in the same direction [with the tight rope], but when the rope…the…string is loose then they'd travel down there, but when it switches direction some of them probably won't go with it. Like they will get lost in that direction and so fewer will travel up that way, because some of them will go off in that other direction (drawing shown in Fig. 11).
> ➢ TARA: Sound kind of, drifts off of it [the loosened, curved string]. Like, the sound waves and… goes into the air versus to the can [on the listener's side].
> Stable–does not spontaneously appear
> o ASHLEY: The sound is created when he talks and then…the sound uses the air particles like as their way of moving.

Stable–does not spontaneously disappear (in vacuum would propagate forever)

> o BIC: (Pause) Um…well yeah, I would assume without air there would be nothing to cut it [sound] down and it would kind of travel…for…ever. I would assume like in a vacuum because there is nothing in a way to stop it so it just keep vibrating forever.
> o JAMES: I am not sure, um…the…there's certainly something in the air but…that makes the sound diminished, because otherwise the sound would go on forever if, if air carried it like in this situation, sound would just keep traveling, so…

APPENDIX C: BLEND MODELS EXPRESSED BY ONE STUDENT ONLY

Vibrating Air model-blend (postinstruction interview).

1. CONTEXT 1a

I: Would anything be different in space with air and in the space without air? […]

HOPE: If there's no molecules anywhere, then I just don't know how sound can be transferred. […]
HOPE: Well the air molecules transfer the sound forward but air molecules keep moving back and forth.

2. CONTEXT 2

I: If the dust particle was previously still and now the speaker starts to talk, will sound from the speaker have any influence on the dust particle?
HOPE: No. […] It moves back and forth just like everything else.

CONTEXT 3a

I: OK. So what happens when the loudspeaker plays slow rhythmic beats, like a slow drum beating you know, it's not a constant tone anymore …
HOPE: Right.
I: But: bum…bum…
HOPE: Same thing. It doesn't move, it just vibrates back and forth.
I: All the time?
HOPE: Yeah.
I: I mean when there is sound and when there is no sound?
HOPE: Right, and the vibrating is what helps make the sound transfer, it's not moving the dust particle anywhere else.
I: OK, so does it move when there is no sound at all?
HOPE: Yeah.
I: …as when the sound propagates?
HOPE: No, I don't know, I should have learned this but I didn't. I don't know… I'm gonna say um…it vibrates back and forth faster the louder the sound, but I have no idea.
I: OK. I mean you say those, dust I mean, the air particles move all the time?
HOPE: Yeah.
I: And so does sound make difference or…?
HOPE: I think sound just uses the air particles as a way to transfer itself.
I: This movement of air particles?
HOPE: Yeah.
I: That is going on?
HOPE: Yeah.
I: OK. So why do we sometimes hear sound and sometimes not?
HOPE: What do you mean? Because no one is talking.
I: Yeah.
HOPE: No one is making the sound.
I: But if air particles move all the time the same way?
HOPE: Well because they all vibrate back and forth in such small little areas. So I would have to be making a noise for it to transfer to you. If I'm not making a noise then, there's nothing to be transferred to you.

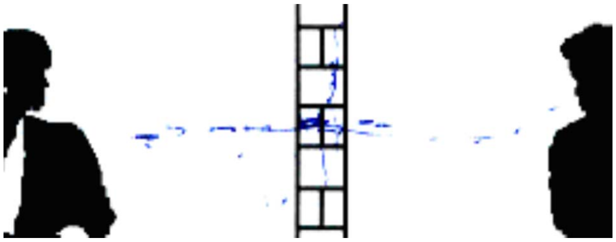

FIG. 12. (Color) Student's drawing over provided template to illustrate the statement (Hope).

3. CONTEXT 4

I: Now question is just how sound gets on the other side [of the wall] in this situation?
HOPE: Same thing. There's particles all over this…through the wall, through the air, and your sound vibrates all these back and forth hitting each other. […]
HOPE: Little molecules just keep on vibrating, just like in the very first page that we did (drawing shown on Fig. 12).
I: OK. So when this speaker talks loudly…
HOPE: Uh huh (Yes).
I: And when he doesn't talk…
HOPE: Uh huh (Yes).
I: How is motion or vibration of particles of the wall different, or is it different?
HOPE: They are not different.

4. CONTEXT 4a

I: So what happens on this microscopic level as the sound reaches the wall?
HOPE: These move back and forth, hitting one another, making them go forward, and so on and so forth. […]
I: OK, good. So does propagation of sound influence motion of the particles of the wall?
HOPE: No.
I: No, they vibrate before…
HOPE: They're vibrating all the time.
I: I mean do they vibrate all the time exactly the same way?
HOPE: Yes.

Ether Model–Blend (Post-Instruction Interview)

5. CONTEXT 1

I: What happens and listener hears the speaker?
JEWEL: OK. There…it causes like…the noise from his mouth like causes the disturbance and they vibrate back and forth…like this (drawing shown on Fig. 13).
I: What vibrates back and forth?
JEWEL: The sound…and then…it goes all the way…until it reaches her ear.I: OK. What are these dots?

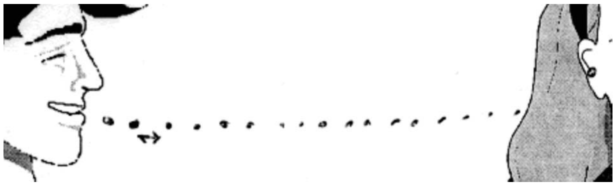

FIG. 13. Student's drawing over provided template to illustrate the statement (Jewel).

JEWEL: They…it doesn't…it's like a noise vibrating, it doesn't like move, it just vibrates and causes the disturbance to go to the air.
I: So what are the dots?
JEWEL: Just the representation of the motion that is going over.
I: OK. And what vibrates?
JEWEL: Just the sound from his mouth…It doesn't really move but just vibrates back and forth so the sound gets from his mouth to her ear.

APPENDIX D: EXAMPLE OF USING CONTEXTUAL CLUES TO CREATE A MODEL WHERE THERE WAS NONE

1. Postinstruction interview; CONTEXT 4

I: So how does this sound get on the other side [of the wall]?
HOPE: Through the vibrations. Like…um…my vibrations…there's molecules everywhere, so the molecules will take the vibrations and transfer the sound to the other side. That's what I think.
[…]
I: So which molecules actually vibrate in the brick?
HOPE: I have no idea.
[…]
I: Do you think that those are air molecules that come into brick or they make brick molecules vibrate?
HOPE: (Long) I have no idea…[…] Um…(pause)…the brick molecules.
I: You would say the brick molecules?

FIG. 14. Student's drawing over provided template to illustrate the statement (Hope).

HOPE: Yeah.
I: OK.
HOPE: But I don't think I believe that's true.
I: Why not?
HOPE: Well I don't know. Because molecules in the bricks are pretty darn solid and I don't really see how they vibrate very much. Then I really don't see how air penetrates them all, that either, so I don't know. We'll stay with the brick molecules.
I: OK.

2. CONTEXT 4a

I: So what happens on this microscopic level as the sound reaches the wall? Now these are brick molecules?
HOPE: Right.
I: And sound comes from speaker's side.
HOPE: OK.
I: What happens?
HOPE: Is there that much space in between the molecules?
I: Yeah, and now this is a microscopic structure.
HOPE: OK. Right.
I: So we just enlarged it really a lot.
HOPE: OK. I think I've changed my answer.
I: OK.
HOPE: I think that air molecules vibrate among the brick molecules, but…do you want me to draw all this for you?
I: Yes sure, please. (drawing shown on Fig. 14).
HOPE: I think they kind of go in and through all of this, bouncing off of the brick molecules and come out on the other side.
I: OK.
HOPE: So they can listen and hear it.

---

[1] R. E. Mayer, Understanding conceptual change, in *Reconsidering Conceptual Change: Issues in Theory and Practice*, edited by M. Limon and L. Mason (Kluwer Academic Publishers, Dordrecht, Netherlands, 2002), pp. 101–111.
[2] J. D. Gobert and B. C. Buckley, Introduction to model-based teaching and learning in science education, Int. J. Sci. Educ. **22**, 891 (2000).
[3] G. Van der Veer, *Mental models of incidental human-machine interaction*. [www] 2000 October 15, 2001 [cited 2002 Jun, 10]; Available from: http://www.cs.vu.nl/~gerrit/mmi9910-report1.doc
[4] I. M. Greca and M. A. Moreira, Mental, physical, and mathematical models in the teaching and learning of physics, Sci. Educ. **86**, 106 (2002).
[5] E. F. Redish, The implications of cognitive studies for teaching physics, Am. J. Phys. **62**, 796 (1994).
[6] A. A. diSessa, Towards an epistemology of physics, Cogn. Instruct. **10**, 105 (1993).
[7] A. A. diSessa, What do "just plain folk" know about physics?, in *Handbook of Education and Human Development: New Models of Learning, Teaching, and Schooling*, edited by D. R. Olson and N. Torrance (Blackwell Publishers, Ltd., Oxford,

1996).

[8] D. Hammer, More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research, Am. J. Phys. **64**, 1316 (1996).

[9] D. Hammer, *Student resources for learning introductory physics.* American Journal of Physics, Physics Education Research Supplement **68**, S52 (2000).

[10] S. Vosniadou, Capturing and modeling the process of conceptual change, Learn. Instr. **4**, 45 (1994).

[11] A. A. diSessa, Why "conceptual ecology" is a good idea, in *Reconsidering Conceptual change: Issues in Theory and Practice*, edited by M. Limon and L. Mason (Kluwer Academic Publishers, Dordrecht, Netherlands, 2002), pp. 29–60.

[12] A. A. diSessa (private communication).

[13] M. J. Merino, Some difficulties in teaching the properties of sounds, Phys. Educ. **33**, 101 (1998).

[14] M. J. Merino, Complexity of pitch and timbre concepts, Phys. Educ. **33**, 105 (1998).

[15] M. C. Wittmann, The object coordination class applied to wave pulses: Analysing student reasoning in wave physics, Int. J. Sci. Educ. **24**, 97 (2001).

[16] M. C. Wittmann, R. N. Steinberg, and E. F. Redish, Making sense of how students make sense of mechanical waves, Phys. Teach. **37**, 15 (1999).

[17] M. C. Wittmann, Making sense of how students come to an understanding of physics: An example from mechanical waves, in *Physics* (University of Maryland, College Park, MD, 1998).

[18] L. Maurines, Spontaneous reasoning on the propagation of sound, in *Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics*, edited by J. Novak [Cornell University, Ithaca, New York, 1993).

[19] L. Maurines, Spontaneous reasoning on the propagation of visible mechanical signals, Int. J. Sci. Educ. **14**, 279 (1992).

[20] C. J. Linder, University physics students' conceptualizations of factors affecting the speed of sound propagation, Int. J. Sci. Educ. **15**, 655 (1993).

[21] C. J. Linder, Understanding sound: so what is the problem? Phys. Educ. **27**, 258 (1992).

[22] C. J. Linder and G. L. Erickson, A study of tertiary physics students' conceptualizations of sound, Int. J. Sci. Educ. **11**, 491 (1989).

[23] C. J. Linder, Tertiary physics: a case study in students' conceptions of sound, in *Proceedings of the Second International Seminar: "Misconceptions and Educational Strategies in Science and Mathematics*, edited by J. Novak (Cornell University, Ithaca, NY, 1987), p. 322–334.

[24] Z. Hrepic, Učenicke koncepcije u razumijevanju zvuka (Students' conceptions in understanding of sound), in *Physics and Polytechnic* (University of Split, Split, Croatia, 1998), p. 154.

[25] C. R. Barman, N. S. Barman, and J. A. Miller, Two teaching methods and students' understanding of sound, Sch. Sci. Math. **96**, 63 (1996).

[26] Z. Hrepic, D. Zollman, and S. Rebello, Identifying students' models of sound propagation, in *Proceedings of 2002 Physics Education Research Conference*, edited by S. Franklin, J. Marx, and K. Cummings (PERC Publishing, Boise, Idaho, 2002).

[27] M. C. Wittmann, R. N. Steinberg, and E. F. Redish, Understanding and affecting student reasoning about sound, Int. J. Sci. Educ. **25**, 991 (2003).

[28] H. Schecker and J. Gerdes, Messung von Konzeptualisierungsfähigkeit in der Mechanik. Zur Aussagekraft des Force Concept Inventory, Zeitschrift für Didaktik der Naturwissenschaften **5**, 75 (1999).

[29] L. Bao and E. F. Redish, Model analysis: Representing and assessing the dynamics of student learning, Phys. Rev. ST Phys. Educ. Res. **2**, 010103 (2006).

[30] K. S. Taber, Multiple frameworks? Evidence of manifold conceptions in individual cognitive structure, Int. J. Sci. Educ. **22**, 399 (2000).

[31] L. Bao, Dynamics of student modeling: A theory, algorithms, and application to quantum mechanics, in *Physics* (University of Maryland, College Park, MD, 1999).

[32] P. G. Hewitt, *Conceptual Physics*, 8th ed. (Addison-Wesley, Reading, MA, 1998), pp. 321–366.

[33] Z. Hrepic, D. Zollman, and S. Rebello, Comparing students' and experts' understanding of the content of a lecture, J. Sci. Educ. Technol. **16**, 213 (2007).

[34] F. Marton, Phenomenography: Describing conceptions of the world around us, Instr. Sci. **10**, 177 (1981).

[35] F. Marton, Phenomenography: A research approach to investigating different understandings of reality, Journal of Thought **21**, 28 (1986).

[36] D. Clerk and M. Rutherford, Language as a confounding variable in the diagnosis of misconceptions, Int. J. Sci. Educ. **22**, 703 (2000).

[37] D. Halliday, R. Resnick, and J. Walker, *Fundamentals of Physics*, 5th ed. (John Wiley and Sons, Inc, New York, 1997).

[38] M. Reiner *et al.*, Naive physics reasoning: A commitment to substance-based conceptions, Cogn. Instruct. **18**, 1 (2000).

[39] T. B. Ward, S. M. Smith, and J. Vaid, Conceptual Structures and Processes in Creative Thought, in *Creative Thought: An Investigation of Conceptual Structures and Processes*, edited by T. B. Ward, S. M. Smith, and J. Vaid (American Psychological Association (APA), Washington, DC 2001), p. 1–27.

[40] G. Fauconnier and M. Turner, *The Way We Think: Conceptual Blending and the Mind's Hidden Complexities* (BasicBooks, New York, NY, 2002).

[41] Z. Hrepic, D. Zollman, and S. Rebello, Eliciting and Representing Hybrid Mental Models, in *Proceedings of Annual Meeting of the National Association for Research in Science Teaching*, 2005, Dallas, TX.

[42] Z. Hrepic, Development of a real-time assessment of students' mental models of sound propagation, in *College of Education* (Kansas State University, Manhattan, KS, 2004), p. 312.

[43] Z. Hrepic, Identifying students' mental models of sound propagation, in *Physics* (Kansas State University, Manhattan, KS, 2002), p. 231.

[44] I. Galili, S. Bendall, and F. M. Goldberg, The effects of prior knowledge and instruction on understanding image formation, J. Res. Sci. Teach. **30**, 271 (1993).

[45] T. Stoddart, *Astronomy: Eliciting Student Ideas*. 1995, Video material produced by Harvard-Smithsonian Center for Astrophysics.

[46] D. T. Brookes and E. Etkina, Using conceptual metaphor and functional grammar to explore how language used in physics affects student learning, Phys. Rev. ST Phys. Educ. Res. **3**, 010105 (2007).

[47] N. S. Podolefsky and N. D. Finkelstein, Analogical scaffolding and the learning of abstract ideas in physics: An example from

electromagnetic waves, Phys. Rev. ST Phys. Educ. Res. **3**, 010109 (2007).

[48] N. S. Podolefsky and N. D. Finkelstein, Use of analogy in learning physics: The role of representations, Phys. Rev. ST Phys. Educ. Res. **2**, 020101 (2006).

[49] P. Johnson-Laird and R. Byrne, *Mental Models Website: A gentle introduction*. 2002 Dec 18, 2000 [cited 2008 Jun, 10]; Available from: http://www.tcd.ie/Psychology/Ruth_Byrne/mental_models/theory.html

[50] J. P. Smith and A. A. diSessa, Misconceptions reconceived: A constructivist analysis of knowledge in transition, J. Learn. Sci. **3**, 115 (1993).

[51] H. Eshach and J. L. Schwartz, Sound Stuff? Naive materialism in middle-school students' conceptionsof sound, Int. J. Sci. Educ. **28**, 733 (2006).

[52] D. A. Norman, Some observations on mental models, in *Mental Models*, edited by D. A. Gentner and A. L. Stevens (Lawrence Erlbaum, Hillsdale, NJ, 1983).

[53] S. F. Itza-Ortiz, S. Rebello, and D. A. Zollman, Students' models of Newton's second law in mechanics and electromagnetism, Eur. J. Phys. **25**, 81 (2004).

[54] V. K. Otero, *The Process of Learning About Static Electricity and the role Of the Computer Simulator* (University of California, San Diego, CA, 2001).

[55] P. G. Hewitt, *Conceptual Physics*, 9th ed. (Addison Wesley, Reading, MA, 2002).

[56] J. W. Creswell, *Qualitative Inquiry and Research Design: Choosing among five traditions* (SAGE Publications, Inc., Thousand Oaks, CA, 1998).