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Misconceptions About Sound Among Engineering Students

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Abstract Our first objective was to detect misconceptions about the microscopic nature of sound among senior university students enrolled in different engineering programmes (from chemistry to telecommunications). We sought to determine how these misconceptions are expressed (qualitative aspect) and, only very secondarily, to gain a general idea of the extent to which they are held (quantitative aspect). Our second objective was to explore other misconceptions about wave aspects of sound. We have also considered the degree of consistency in the model of sound used by each student. Forty students answered a questionnaire including open-ended questions. Based on their free, spontaneous answers, the main results were as follows: a large majority of students answered most of the questions regarding the microscopic model of sound according to the scientifically accepted model; however, only a small number answered consistently. The main model misconception found was the notion that sound is propagated through the travelling of air particles, even in solids. Misconceptions and mental-model inconsistencies tended to depend on the engineering programme in which the student was enrolled. However, students in general were inconsistent also in applying their model of sound to individual sound properties. The main conclusion is that our students have not truly internalised the scientifically accepted model that they have allegedly learnt. This implies a need to design learning activities that take these findings into account in order to be truly efficient.

Keywords Misconceptions · Mental models of sound · Sound propagation · Mental-model inconsistency · Engineering students

Introduction

From the point of view of constructivist teaching, there is considerable consensus regarding the need to have a detailed image of students' understanding of a physical phenomenon before it is formally studied. This must be taken into account when one is planning and implementing learning activities aimed at the acquisition of scientifically accepted knowledge. Indeed, many cognitive psychologists and constructivists have stated that people construct new knowledge based on what they already know and believe, even if parts of this knowledge and understanding, which we shall call 'prior ideas' or 'misconceptions', are not consistent with scientific conceptions (Çalik and Ayas 2005; Chang et al. 2007; Eshach and Schwartz 2006; Wittmann et al. 2003).

Their consideration is also important in order to prevent traditional teaching resources from becoming 'traps', such as those graphs, illustrations and texts that could reinforce prior ideas that are not scientifically acceptable (Leite and Afonso 2001; Linder 1993; Wittmann et al. 2003). Science fiction films are another popular 'trap' as a possible source of misconceptions (Barnett et al. 2006). Furthermore, when using analogies, such as using water waves to explain sound waves, one must bear in mind the considerable limitations and potential 'traps' thereof, despite the proven scientific and didactic value of analogies (Podolefsky and Finkelstein 2006, 2007). They will be productive only when used as 'bridging analogies'. To this end, instructors must choose a bridging strategy that builds on students'

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prior ideas, taking into account the many ways that representations can be interpreted, so as to create a conceptual blend of productive representations (see also Yilmaz and Eryilmaz 2010). The effect of conceptual change pedagogy on students' alternative conceptions about different topics in physics has been reported newly by Çalik et al. (2010c), Er Nas et al. (2012) and Coruhlu-Senel et al. (2012). In contrast, the use of IT tools to supplement traditional teaching activities is not in and of itself effective with regard to challenging misconceptions about sound, but rather requires additional supports (Houle and Barnett 2008).

Hamza and Wickman (2008) have played down the influence of misconceptions on learning science in secondary education, at least in some fields (electrochemistry). In contrast, according to Smolkin et al. (2009), knowing the possible misconceptions and taking them into account is important for science teachers in general before entering the classroom (Schmidt 1997), especially for science teachers who use trade books.

Misconceptions about sound have been quite widely investigated in primary and secondary education (e.g. Chang et al. 2007; Eshach and Schwartz 2006; cf. misconception database by Duit 2009), but only scarcely so in engineering education (e.g. Houle and Barnett 2008; Hrepic 2004). Some of the co-authors have previously investigated prior ideas in other fields of physics in first-year students (Periago and Bohigas 2005).

First, misconceptions about sound are expressed in scientifically unacceptable mental models of the nature of sound, as well as in relation to specific aspects of sound, such as the linking of pitch (frequency) and volume (intensity) and/or distance travelled, the assumption that frequency depends on the propagation medium, or the assumption that the speed of sound depends on different parameters, such as the speed of the sound source, frequency or intensity. In the "Discussion" section, we will establish the current state of the art by comparing our results with those of other researchers. One important finding is that mental-model inconsistency on the part of students has been found in virtually all quantitative research about prior ideas, including at the university level.

The specific objective of this study was to verify how (qualitative aspect) and, only secondarily, to what extent (quantitative aspect) the aforementioned misconceptions are expressed in a sample of engineering students. Therefore, when considering the results, one must take into account the rather qualitative nature of this research, in which capturing the richness of students' responses and the possible relationships between misconceptions and mental-model inconsistencies was of more interest than determining the exact percentage of students expressing any given prior idea.

Experimental Aspects of the Research

Sample Description

The sample consisted of 40 senior university students from different branches of engineering who were about to begin an elective subject on acoustics, taught yearly from 2008 to 2010 (three semesters). The curricula for both their secondary education and the first-year subject of engineering physics included simple harmonic motion and waves in general. Furthermore, depending on their chosen branch, some, such as those studying telecommunications, had received broader instruction on those aspects of sound most closely related to their specific branch. In other branches, such as computing or chemistry, sound is not addressed by the rest of the curriculum.

As stated above, the quantitative aspect is only of secondary interest here, since this study focuses on the qualitative relationships between each student's mental model and his/her (other) misconceptions on sound, taking into account his/her specific branch of engineering. So, although the number of students (40) would certainly be low for a quantitative study of the occurrence of every misconception considered, qualitative studies generally use small sample sizes, as e.g. in Jakobsson et al. (2009), Hrepic et al. (2010), Azar (2010), and Çalik (2011).

Our research assumes that, at the university level, students have already 'learnt' that sound consists of vibrations, although we did consider the possibility that, in practice, this notion remains so vague in students' minds that it is no more than a concept they have memorised but not assimilated in terms of its actual physical meaning.

Methodology: Questionnaire Description

The needs and methods of exploring students' conceptions and conceptual change, in particular the paper and pencil surveys (open-ended questions and multiple-choice questions), have been studied in detail by Çalik et al. (2005) and Kurnaz and Çalik (2009). These needs and the significance of this exploration are obvious in the context of our study as well.

The questionnaire used for this study consisted mainly of open-ended questions, combined with a limited number of closed-ended (multiple-choice) questions. For the former, each student was asked to provide an explanation using his/her model of sound. This was in keeping with the technique used by Hrepic (1999) and with two-tier questionnaires (Chang et al. 2007), since, in both these studies and others (e.g. Hrepic 2004; Hrepic et al. 2010), this method has proved to provide concrete and useful information.

To prevent the pitfalls reported by Jakobsson et al. (2009) for other studies on misconceptions, students were given unlimited time to answer and the questionnaire was written in everyday language, avoiding specific scientific terms. Also in contrast to some practices reported by these authors, answers were not categorized strictly according to their exact wording (where or not they were strictly scientifically acceptable or not), but by taking each student's full set of answers into account, in the very few cases that the answer contained any ambiguity. Indeed, the categorization of answers to the open-ended questions was made easy by the fact that already from the first semester of our study on, most of the answers expressed a limited set of clear prior ideas. We were thus also able to prevent any false mental-model inconsistency due to misinterpretations of the language used in the questions regarding different contexts or scenarios, as described by Alonzo and Steedle (2009).

The prior ideas studied with this questionnaire mainly concerned the microscopic model of sound and, in relation thereto, the relationships between sound parameters such as pitch, frequency, speed, distance travelled, intensity and the propagation medium.

When the questionnaire was handed out to the students, it was stressed that it was intended to improve learning activities for the subject and would not, under any circumstances, be marked, whether or not the answers were academically acceptable. As an incentive to complete the questionnaire, a small bonus was added to the mark simply for filling it out by the established deadline of about 3 days before the subject began. About one-fourth of the students filled it out in person (in about 20–30 min). Although they were encouraged to ask for explanations of the questions, none did. The rest of the students answered the questionnaire remotely by e-mail or through the Virtual Campus, requiring 20–45 min, according to their own reports.

Many of the questions were taken or adapted from existing publications about prior ideas on acoustics at other education levels. This enables comparison of our results with those from the literature, where applicable, despite possible differences in education level. In addition, every question was examined and discussed previously by all four authors and other experienced colleagues, and after its use in the first of the three semesters mentioned above, only minor corrections were deemed necessary after evaluating the coherence between answers and questions, in order to ensure the reliability of the questionnaire.

The first five questions (Q1–Q5) addressed students' mental models of sound at the microscopic level more directly in different scenarios: production; transmission in air, in solids and through a solid wall; and perception in the ear. The central role of mental models in science education as well as the difficulties in modelling physical concepts have been widely investigated (e.g. Coll and Treagust 2003; Coll 2005; Teodoro 2006; Gokdere and Çalik 2010). To delimit the specific mental models proposed, we used the conclusions of Hrepic (2004), Hrepic et al. (2010) and Linder and Erickson (1989) (basic models and model hybridisations).

Thus, the four proposed models were basically those proposed by Hrepic (2004) (Questions Q1–Q4) and, in part, Chang et al. (2007) (Question Q5), from whom we took the questions almost literally. Following the same order as the graphics in Fig. 1, they were as follows:

A. Vibration of air or solid-wall molecules, which is propagated to neighbouring molecules.
B. Air molecules that move through other air molecules or any solid-wall molecules they may hit.
C. Sound particles moved with the help of the previous random motion of the air or solid-wall molecules, which transfer the sound particles from one molecule to the next.
D. Sound particles that move through air or solid-wall particles, causing them to vibrate.

By way of example with regard to these first five questions, Fig. 1 shows Question 2 (scenario: sound propagation in air).

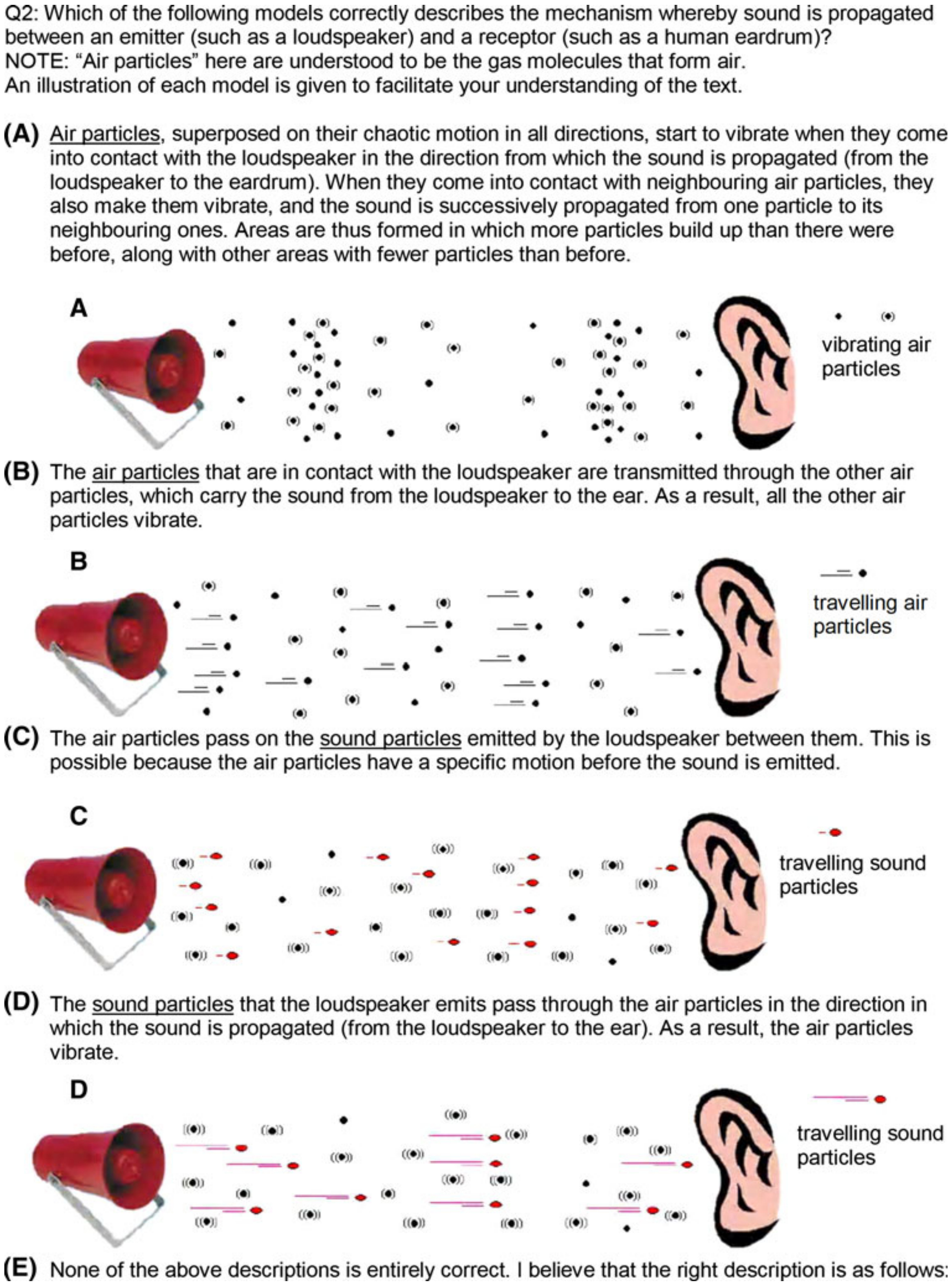
Model A is the only scientifically accepted model of sound. Thus, using the terminology employed in some articles on misconceptions about sound (e.g. Wittmann et al. 2003), the scientifically accepted 'event-like' properties of sound can be inferred from Model A, whereas 'object-like' properties would be inferred from Models B to D, all of which attribute a corpuscular nature to sound to a greater or lesser extent in the form of frictional, containable (i.e. localised rather than spread, like waves), transitional (i.e. able to move or be moved), inertial and other corpuscular properties (Eshach and Schwartz 2006).

Two further open-ended questions, Q6 and Q14, addressed prior ideas regarding the relationship between pitch and frequency, such as the number of vibrations per second produced in the eardrum.

Example (Q14): A single musical instrument, e.g. a trumpet, emits a high-pitched sound followed by a low-pitched one. What is the difference between the types of vibrations these sounds produce in our eardrum?

Questions Q7 and Q8, also open-ended, addressed prior ideas regarding the dependence of sound frequency on the distance travelled (Q7) and on sound intensity (Q8). These two aspects are related, as seen in the answers obtained.

Example (Q8): The same drum from the last question is given a gentle hit and then a hard one. The first sound will be soft and the second one loud. If, when generating the first sound, the drum head vibrates 80 times a second, state whether it produces more, the same number or fewer



Q2: Which of the following models correctly describes the mechanism whereby sound is propagated between an emitter (such as a loudspeaker) and a receptor (such as a human eardrum)?
NOTE: "Air particles" here are understood to be the gas molecules that form air.
An illustration of each model is given to facilitate your understanding of the text.

(A) Air particles, superposed on their chaotic motion in all directions, start to vibrate when they come into contact with the loudspeaker in the direction from which the sound is propagated (from the loudspeaker to the eardrum). When they come into contact with neighbouring air particles, they also make them vibrate, and the sound is successively propagated from one particle to its neighbouring ones. Areas are thus formed in which more particles build up than there were before, along with other areas with fewer particles than before.

(B) The air particles that are in contact with the loudspeaker are transmitted through the other air particles, which carry the sound from the loudspeaker to the ear. As a result, all the other air particles vibrate.

(C) The air particles pass on the sound particles emitted by the loudspeaker between them. This is possible because the air particles have a specific motion before the sound is emitted.

(D) The sound particles that the loudspeaker emits pass through the air particles in the direction in which the sound is propagated (from the loudspeaker to the ear). As a result, the air particles vibrate.

(E) None of the above descriptions is entirely correct. I believe that the right description is as follows:

Fig. 1 One of the first five questions (Q2) on the mental model of sound (scenario: sound transmission in air) (taken from Hrepic 2004). The graphic representations correspond to the four basic models mentioned in the text and are shown in the same order

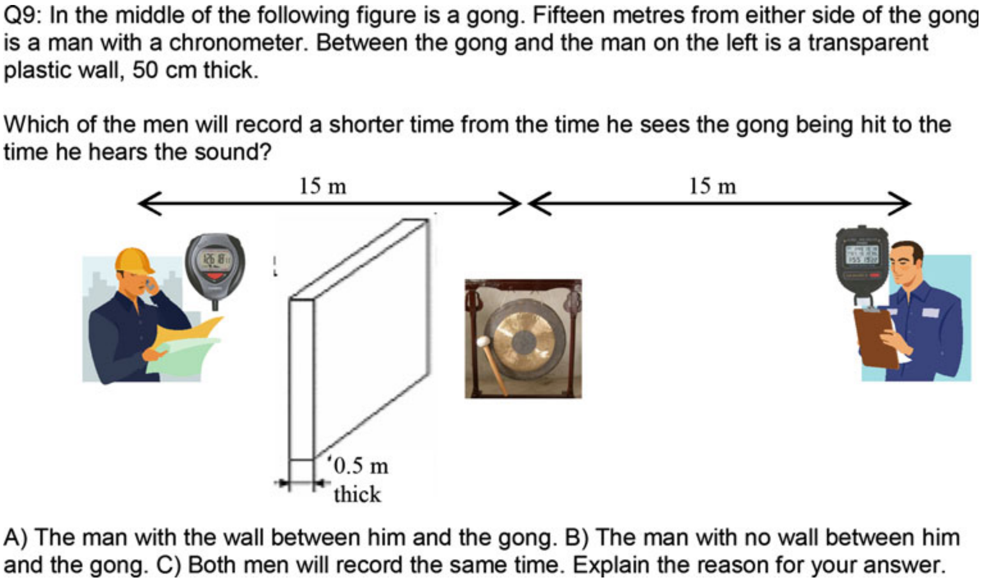
vibrations per second when generating the second (loud) sound. Please explain your answer.

Questions Q9, Q10, and Q11 were multiple-choice questions, but students were asked to justify their answers. These questions were also adapted from Hrepic (2004). They explored prior ideas regarding changes in sound speed and frequency when the sound must go through a solid wall (Q9 and Q10 respectively) and changes in sound speed when the sound source is moving (Q11). By way of example, Fig. 2 shows Q9 and Fig. 3 shows Q11.

Finally, Questions Q12 and Q13 addressed the dependence of sound speed on pitch (frequency) and sound intensity (volume), respectively. By way of example, Fig. 4 shows Q12.

Results

Tables 1 and 2 summarise the results for the mental model of sound (Questions Q1–Q5, Table 1) and some related properties of sound (Questions Q6–Q14, Table 2). In both tables, the student rows are ordered, first, by the number of deviations from the scientifically accepted model of sound and, second, by the number of inconsistencies between the

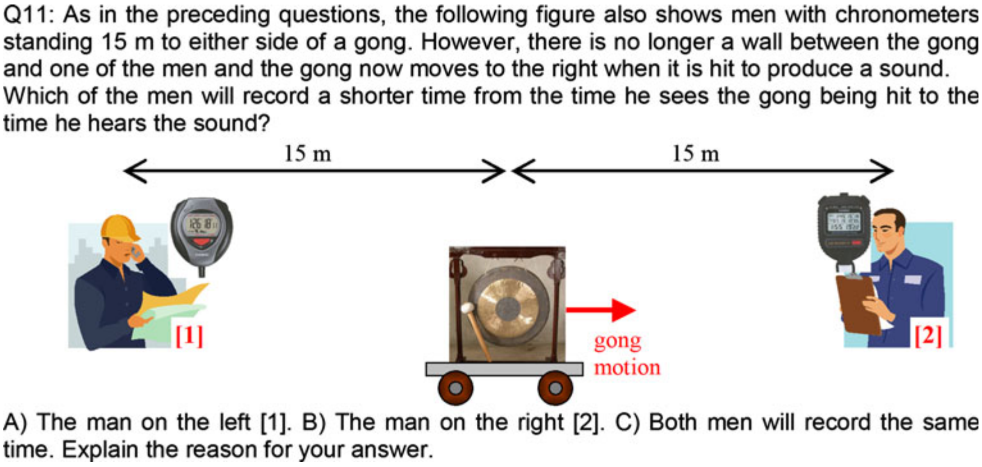


Q9: In the middle of the following figure is a gong. Fifteen metres from either side of the gong is a man with a chronometer. Between the gong and the man on the left is a transparent plastic wall, 50 cm thick.

Which of the men will record a shorter time from the time he sees the gong being hit to the time he hears the sound?

A) The man with the wall between him and the gong. B) The man with no wall between him and the gong. C) Both men will record the same time. Explain the reason for your answer.

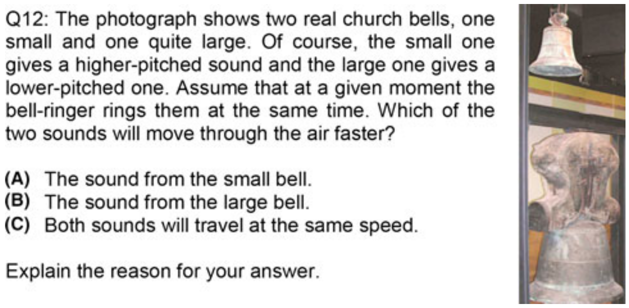
Fig. 2 Question Q9 on the relationship between sound speed and change of medium with a solid wall (adapted from Hrepic 2004)



Q11: As in the preceding questions, the following figure also shows men with chronometers standing 15 m to either side of a gong. However, there is no longer a wall between the gong and one of the men and the gong now moves to the right when it is hit to produce a sound. Which of the men will record a shorter time from the time he sees the gong being hit to the time he hears the sound?

A) The man on the left [1]. B) The man on the right [2]. C) Both men will record the same time. Explain the reason for your answer.

Fig. 3 Question Q11 about the relationship between the speed of sound and the speed of the sound source (adapted from Hrepic 2004)



Q12: The photograph shows two real church bells, one small and one quite large. Of course, the small one gives a higher-pitched sound and the large one gives a lower-pitched one. Assume that at a given moment the bell-ringer rings them at the same time. Which of the two sounds will move through the air faster?

(A) The sound from the small bell.
(B) The sound from the large bell.
(C) Both sounds will travel at the same speed.

Explain the reason for your answer.

Fig. 4 Question Q12 about sound speed and pitch (frequency)

stated properties and each student's dominant model of sound. The fields show how the answers to each question were classified. A green (or dark grey) background indicates that an answer agrees with the scientifically accepted answer, whereas a yellow (or light grey) background was used to designate the most frequent scientifically unacceptable answers (or answer categories).

Questions Q1–Q5: Mental Models of the Nature of Sound

An initial glance at Table 1 reveals a predominance of green (or dark grey) cells, i.e. a predominance of the scientifically accepted model in the individual answers.

However, the inconsistency between the individual answers provided by each student also becomes obvious in most cases as one moves down the table.

The predominant model misconception is the notion that sound is propagated by travelling air particles, even through solids. This was especially true in Question 4 (propagation through a wall).

Examples of answers (Question Q3):

> 'I think that the air or sound particles hit the eardrum at a given speed. This speed determines how pronounced the sound is.' (Answer classified as Model B, travelling air particles, since this mechanics student also used that model in other scenarios.)

Table 1 Overview of the results for the different students enrolled in different engineering programmes, concerning the mental model of sound

		Model of sound					
Scenario (Q1-Q5):		sound emission	propagation in air	sound reception	propagation in a wall	propag. closed contain.	Deviations from accepted model
Question:		**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	
Students							
S01	Telecomm.	✓	✓	✓	✓	✓	0
S02	Electronics	✓	✓	✓	✓	✓	0
S03	Telecomm.	✓	✓	✓	✓	✓	0
S04	Electronics	✓	✓	✓	✓	✓	0
S05	Mechanics	✓	✓	✓	✓	✓	0
S06	Computing	✓	✓	✓	(✓)	(✓)	0
S07	Telecomm.	✓	✓	✓	✓	✓	0
S08	Telecomm.	✓	✓	✓	✓	✓	0
S09	Electricity	✓	✓	(✓)	✓	✓	0
S10	Electricity	✓	✓	(✓)	✓	✓	0
S11	Telecomm.	MS/TS	✓	✓	✓	✓	1
S12	Civil Engin.	TS	✓	✓	✓	✓	1
S13	Mechanics	MA	✓	(✓)	✓	✓	1
S14	Mechanics	MA	✓	(✓)	✓	✓	1
S15	Telecomm.	MA	✓	✓	(✓)	✓	1
S16	Civil Engin.	✓	✓	(✓)	MA	✓	1
S17	Electronics	✓	✓	✓	MS	✓	1
S18	Telecomm.	✓	✓	✓	TS	✓	1
S19	Civil Engin.	✓	✓	✓	MA	✓	1
S20	Thermoeng.	✓	✓	(✓)	(✓)	[2]	1
S21	Mechanics	✓	✓	✓	MS	✓	1
S22	Telecomm.	✓	✓	(✓)	✓	[1]	1
S23	Electricity	✓	MA	✓	MA	✓	2
S24	Electronics	✓	MA	MA	✓	✓	2
S25	Aeronautics	✓	✓	(✓)	MS	[2]	2
S26	Telecomm.	✓	✓	✓	MS	[2]	2
S27	Electricity	✓	✓	✓	MS	[2]	2
S28	Electronics	✓	MS	✓	✓	[1]	2
S29	Computing	MA	MA	(✓)	✓	✓	2
S30	Mechanics	✓	✓	(✓)	TS	[2]	2
S31	Electronics	✓	TS	(✓)	✓	[1]	2
S32	Telecomm.	✓	✓	(✓)	TS	[2]	2

Table 1 continued

S33	Telecomm.	MA	MA	MA	✓	✓	3
S34	Mechanics	MA	MA	(✓)	TS	✓	3
S35	Electricity	MA	✓	(✓)	MS	[1]	3
S36	Mechanics	MA	✓	MA/MS	MA	✓	3
S37	Aeronautics	MA	MA	(✓)	MA	[1]	4
S38	Chemistry	MA	✓	-	MA	[2]	4
S39	Mechanics	MA	MA	MA	MS	✓	4
S40	Computing	MA	MA	-	MA	[1]	5

MA = Movement of air particles (e.g. “The vibrating air particles pass through the particles of our ear membrane …“)

MS = Movement of sound particles (“The sound particles emitted by the loudspeaker pass through the air particles …”)

TS = Transmission of sound particles (“The air particles pass on the sound particles emitted by the loudspeaker between them…”)

[1] Sound never passes through a wall which completely encloses the sound source.

[2] Sound passes just partly through holes in a wall completely enclosing the sound source.

(In yellow: respective most frequent misconception)

✓ = clearly according to the accepted model

(✓) = compatible with the scient. accepted model

> ‘The vibrating air particles pass through the particles of our ear membrane [eardrum], and this is the vibration received by the nerve cells […]’

According to how the rows are ordered in Table 1, we also obtain the following result: by engineering programme, the number of deviations from the scientifically accepted model increases from a minimum for telecommunication, civil engineering and electronics programmes to a maximum for programmes such as computing, chemistry or aeronautics. (All are three-year engineering programmes, except civil engineering, which is a 5-year programme.)

Questions Q6 and Q14: Relationship Between Pitch and Sound Frequency

Table 2 shows that here, too, the majority of answers to both questions were scientifically acceptable and consistent with one another. This can likely be attributed to the students’ educational background. The clearest exceptions were three mechanics students, one computing student and one telecommunication student, who had expressed a hybridised model of sound in Questions Q1–Q5.

As seen in Table 2, the prior idea expressed in the main scientifically unacceptable answers was that the greater the intensity, the greater the frequency. For example:

> [Q6] ‘The [typical sound produced by a] man [produces more vibrations per second], because his voice is deeper and louder.’ (Industrial electricity student who used the scientifically accepted model—with no inconsistencies—in Questions Q1 to Q5; in addition, this student seems to associate a man’s typically ‘deeper’ voice with its ‘louder’ sound.)
>
> [Q6] ‘The sound produced by a woman […] Therefore, a high-pitched sound causes the eardrum to vibrate more intensely.’ (The answer is scientifically acceptable, but the explanation is not.)

Table 2 Overview of the results for the same students as in Table 1, concerning different related properties of sound

	Sound frequency					Sound speed				Inconsistencies in Q6 to Q14 regarding dominant model
	Pitch versus frequency		Freq. versus distance	Freq. versus intensity	Freq. versus medium	depending on medium	dep. on source motion	depending on frequency	depending on intensity	
	Q6	**Q14**	**Q7**	**Q8**	**Q10**	**Q9**	**Q11**	**Q12**	**Q13**	
Stud.										
S01	✓	✓	✓	✓	✓	✓	✓	✓	✓	0
S02	✓	✓	✓	✓	✓	✓	✓	✓	✓	0
S03	✓	(✓)	✓	✓	✓	✓	(✓)	✓	✓	0
S04	✓	✓	✓	✓	✓	✓	✓	✓	✓	0
S05	✓	(✓)	✓	✓	✓	[12]	✓	✓	✓	1
S06	✓	✓	✓	✓	✓	[14]	[15]	✓	✓	2
S07	✓	(✓)	✓	✓	[3]	✓	[17]	✓	✓	2
S08	✓	✓	[3]	[3]	[3]	[13]	✓	✓	✓	2
S09	[3]/[5]	✓	[7]	[3]	[3]	[12]	[15]	✓	✓	4
S10	(✓)	(other)	[10]	[10]	[10]	[12]	[15]	[18]	(other)	5
S11	✓	✓	✓	✓	✓	✓	✓	✓	✓	0
S12	✓	✓	✓	✓	✓	[14]	✓	✓	✓	1
S13	✓	✓	✓	✓	✓	[14]	✓	✓	✓	1
S14	✓	✓	✓	✓	✓	[14]	✓	✓	✓	1
S15	✓	✓	[3]	[3]	[3]	[13]	✓	✓	✓	2
S16	✓	✓	✓	[3]	(✓)	[12]	✓	✓	✓	2
S17	✓	✓	✓	✓	[7]	[14]	[15]	✓	✓	3
S18	✓	✓	[3]	✓	✓	[12]	✓	[18]	✓	3
S19	✓	✓	[3]	[3]	[3]	[21]	✓	[18]	✓	3
S20	✓	✓	✓	✓	✓	[12]	[15]	[18]	✓	3
S21	✓	✓	✓	✓	[3]	✓	[15]	(other)	✓	3
S22	✓	✓	[3]	✓	✓	[12]	[17]	[3]+[21]	[21]	4
S23	✓	✓	✓	✓	✓	✓	✓	✓	✓	0
S24	✓	✓	✓	✓	✓	[14]	✓	✓	✓	1
S25	✓	✓	(✓)	✓	✓	✓	✓	[18]	✓	1
S26	[6]	[6]	[3]	[3]	[3]	[13]	✓	✓	✓	3
S27	✓	[18]	[3]	[3]	[3]	[13]/[3]	✓	[18]	[18]	3
S28	✓	[3]	[3]	[3]	[3]	[12]	✓	[18]	✓	3
S29	[3]	[3]	[3]	[3]	[3]	[12]	[16]	✓	✓	3
S30	✓	[3]	[3]	[3]	[3]	[12]	✓	[18]	✓	3
S31	(✓)	[3]	[3]	[3]	[3]	[12]	✓	[18]	[21]	4
S32	✓	✓	[8]	✓	[3]	[12]	[15]	✓	✓	4
S33	✓	✓	(✓)	[3]	[3]	[14]	[15]	✓	✓	(not applic.)
S34	[18]	[18]	✓	(other)	(other)	✓	(other)	[18]	[18]	(not applic.)
S35	✓	(✓)	(✓)	✓	[3]	[13]	✓	[18]	✓	(not applic.)
S36	[4]	[4]	[4]+[9]	[10]	[11]	[12]	[15]	[19]	[21]	(not applic.)
S37	✓	✓	✓	[3]	✓	[14]	[17]	✓	✓	(not applic.)
S38	✓	✓	-	(✓)	[3]	[13]	[17]	✓	✓	(not applic.)
S39	[5]	[6]	[3]	✓	(✓)	[14]	[15]	[20]	[21]	(not applic.)

Table 2 continued

S40	✓	✓	[3]	[3]	[3]	[13]		[15]		✓		✓	(not applic.)

[3] A greater sound intensity is linked to a higher frequency.
[4] The higher the frequency, the faster the sound or air particles travel.
[5] A deeper pitch has more frequency.
[6] A deeper pitch has less intensity.
[7] More frequency because of greater vibration concentration in space.
[8] Vibration wears out in its way.
[9] Particles gradually loose speed with the travelled distance.
[10] More intensity gives more amplitude, and therefore less frequency.
[11] More frequency, because the wall reduces the intensity.

[12] Same speed in air as in a solid.
[13] Sound looses speed because the change of medium is an obstacle.
[14] Sound goes more slowly in solids.
[15] Greater speed in the moving direction of the source.
[16] Vibrations find it harder to arrive if the source is moving away.
[17] Shorter way of the sound if the source is approaching.
[18] The greater the frequency, the greater the speed (≈ [4]).
[19] The smaller bell drives forward less air particles, which then have more speed.
[20] The big bell has a larger size and therefore its sound has more speed.
[21] The more the intensity, the more the speed.

> [Q14] '[The difference between the high- and low-pitched sound lies] in the amplitude or width of the waves produced per second. A high-pitched sound produces a wider wave than a low-pitched one.' (Computer engineering student whose sound model was a hybridisation of the 'travelling air molecules' model and the scientifically accepted model in Questions Q1 to Q5.)

In one case, both answers revealed an association between (higher) pitch and higher emission speed of the air molecules as components of the emitted sound:

> [Q6] 'I think the woman's and the child's voice [produce more vibrations per second], because the sound is higher-pitched and the particles come out at a higher speed.'
> [Q19] '[The difference between the high- and low-pitched sound lies] in the vibration of the eardrum and the speed with which the air particles come out.' (Mechanics student whose sound model was a hybridisation of the 'travelling air molecules' model and the scientifically accepted model.)

Question Q7: Relationship Between Sound Frequency and Distance Travelled

As shown in Table 2, only about half the students (22 out of 40) gave a scientifically acceptable answer. Seven of these students had expressed the scientifically accepted model of sound in a fully consistent way (Questions Q1–Q5), i.e. applied it to all scenarios. On the opposite end of the spectrum, another student (of aeronautics) had consistently used one scientifically unacceptable model ('travelling air particles') in virtually all scenarios.

Of the scientifically incorrect answers, the following deserve special mention:

> '[The vibrations per second] increase because they must reach the brain.' (Electronics student with a scientifically acceptable model of sound with only one clear model inconsistency.)
> I.e. The greater the distance, the higher the frequency needs to be in the eardrum for the brain to perceive the sound.
> 'The number of vibrations [per second] decreases, because part of the vibration energy is lost. The sound thus arrives with a different number of vibrations depending on how far away you are.' (Telecommunications student using a scientifically accepted model of sound with no inconsistencies!)
> This answer is the opposite of the preceding one, but may rely on the same underlying idea, i.e. that frequency is linked to intensity ('energy of sound'): the greater the distance, the lower the intensity, and the lower the intensity, the lower the frequency.
> 'When the vibrations reach the eardrum, they increase, because they are more concentrated in a smaller space.' (Industrial electricity student who also used the scientifically accepted model of sound with no inconsistencies!)
> Despite using the fully accepted model of sound, this answer reveals the attribution of an object-like property to the sound 'vibrations' (which would be

capable of concentrating in a smaller area) or, at least, confusion between frequency and intensity as in the previous answer.

As for the main misconception, Table 2 shows that about one-third of the students also linked frequency to intensity, which decreases with distance. One of them (a telecommunications student using an inconsistent hybridisation of 'sound particles' and the scientifically accepted model) gave the following explanation:

> 'Vibration wears out as it travels.'

which indicates the attribution of object-like properties to sound.

To sum up, associations between distance and intensity (scientifically accepted) and between intensity and frequency, understood as the number of vibrations per second, are remarkably common, as are ideas resulting from an at least partially object-like conception of sound.

It is likewise remarkable that some students who had previously expressed the scientifically accepted model, some without any inconsistencies, expressed ideas based on an object-like conception of sound here.

Question Q8: Relationship Between Frequency and Intensity

According to Table 2, only about half the sample gave scientifically acceptable answers (i.e. frequency is independent of intensity). However, a comparison of Tables 1 and 2 reveals a relatively high number of inconsistencies with the respective model of sound.

Moreover, some explanations relied on conceptions that are not scientifically acceptable. This is the case in the following answer, where wavelength is confused with vibration amplitude:

> 'It will produce the same [number of vibrations per second], but the vibrations will have a longer wavelength.' (Telecommunications student using a scientifically accepted model of sound, except for two inconsistencies based on the 'transmission of sound particles').

The main misconception was held by almost all other students (with only two exceptions), who attributed greater frequency to greater intensity. For example (two further examples are provided in the following section):

> '[Greater intensity produces] more vibrations per second, because the frequency will be higher' (Two electronics students using a model of sound with two clear inconsistencies.)

In contrast, the two final unacceptable answers seem to attribute lower frequency to higher intensity:

> 'Fewer [vibrations per second]. When hit harder, the membrane travels farther and moves more air or particles. It is therefore louder.' (Mechanics student using a 'travelling air' model of sound hybridised with the scientifically accepted model in two scenarios.)

Question Q9: Comparison Between the Speed of Sound in a Solid and in Air

As seen in Table 2, only a minority (10 out of 40) of the answers regarding this comparison were scientifically acceptable, including the explanation (higher speed in a solid). More students (14) expressed the idea that speed is the same in a solid as in air. Many of them added that all that changes is the sound intensity.

Nine other students believed that sound travels more slowly in a solid (or more quickly in air), expressing intriguing prior ideas based on an object-like conception of sound. For example:

> '[…] [in air], the vibration will arrive more quickly, since it does not need to change media.' (Telecommunications student with a consistent scientifically accepted model of sound!)
>
> 'Since there is no obstacle between the gong and the man, the sound will travel at about 340 m/s. However, when passing through the wall, the sound will go more slowly and take a little longer.' (Aeronautics student using a 'travelling air' model of sound with no hybridisation with the scientifically accepted model.)

The first example is especially revealing, since this student had previously expressed the scientifically accepted model of sound with no inconsistencies, but now seems to perceive a change of medium as an obstacle that sound must overcome, causing it to lose speed. The second example explicitly mentions an 'obstacle' leading to a loss of speed, as if sound were imbued with some object-like property that caused it to slow down upon contact with a solid obstacle.

Remarkably, these misconceptions concerning sound speed in a medium were relatively common in the sample of students, even among those students who had expressed the scientifically accepted model of sound with no or one deviation at most. Indeed, half the students with no deviation from this model now showed this misconception. (This result is compared with those of other authors in the Section "Discussion—Sound speed in air versus in solids", below.)

Question Q10: Relationship Between Frequency and the Propagation Medium

According to Table 2, about half the students (19 out of 40) gave the scientifically accepted answer and explanation. In contrast, about the same number of students (17) expressed the idea that the sound that does not need to go through the wall will have a higher frequency because it will be more intense. For example:

> '[…] as before, more energy is lost when the sound changes medium. Therefore, fewer vibrations [per second] will reach the man behind the wall.' (Telecommunications student with a consistent and scientifically accepted model of sound!)
>
> 'More vibrations [per second], because the sound does not need to pass through any obstacles and will arrive with greater intensity.' (Computer engineering student using a model of sound that hybridised the 'travelling air particles' model with the scientifically accepted model.)

One student expressed the opposite idea for a second time (as in Question Q8), namely, that the greater the intensity, the lower the frequency (higher frequency of the sound going through the wall):

> '[…] I think [that fewer vibrations per second will reach] the man behind the wall, [because] the noise [i.e. the sound] will not be as intense (as with the drum in Question 8).' (Mechanics student using a hybridisation of the scientifically accepted model and the 'travelling air particles' model.)

Question Q11: Relationship Between the Speed of Sound and the Speed of the Sound Source

About half the students (23 out of 40) gave a scientifically acceptable answer (the speed of sound is independent of the speed of the sound source), but only six had previously expressed the scientifically accepted model of sound with no inconsistencies. Moreover, although the brunt of one of these answers was scientifically acceptable, it contained a comment that revealed a remarkable prior idea that lies beyond the scope of this paper, namely, that the intensity of sound is greater in the direction of the movement of the sound source:

> '[Both men] will record the same time. The difference is that the one on the left will hear it with less intensity, and the one on the right with more intensity.' (Telecommunications student with a scientifically accepted model, except for solids, based on the 'transmission of sound particles'.)

All remaining students stated that the man on the right would record a shorter time (higher speed of sound to the right, in the direction the gong is moving). Some of these answers stood out, given their inconsistency with the model of sound expressed in the first five questions. For example:

> '[…] because the particles are also moving to the right.' (Industrial electricity student)

This case is particularly telling, as this student had used the scientifically accepted model in each of the first five questions. In contrast, in this answer he seems to be operating on the prior idea that sound consists of particles that move in a given direction, namely, that in which the sound is propagated. An equivalent answer was given by a mechanics student, who made explicit mention of particles moving in the same direction; however, this student had previously expressed a hybridisation of the scientifically accepted model and the 'travelling air particles' model. Although other answers do not explicitly mention particles, they attribute object-like properties to sound to a greater or lesser extent. For example:

> 'In addition to the speed of sound, one must add the relative speed of the gong with regard to the ground.' (Telecommunications student using a hybridisation of the scientifically accepted model and the 'transmission of sound particles' model.)

The following answer is another example of how event-like properties (such as the oscillatory nature of sound) can be mixed with object-like ones, which reveals the persistence of the aforementioned prior idea:

> 'The "birthplace" of the vibrations is moving away from the man on the left, that is, it is harder for the vibrations to reach this man.' (Computer engineering student using a hybridisation of the scientifically accepted model and the 'travelling air' model.)

Question Q12: Dependence of the Speed of Sound on Frequency

As seen in Table 2, well over half the students gave the scientifically accepted answer, including the explanation (speed is independent of frequency). When viewed in combination with Table 1, Table 2 also shows that there is a better qualitative correspondence between the acceptable answers to this question Q12 and the acceptable answers on the model of sound (Questions Q1–Q5) than for Questions Q7–Q11.

Additionally, about one-third of students attributed higher speed to a higher frequency, sometimes based on reasoning that seemed to attribute object-like properties to sound. For example:

> '[The sound from the small bell moves at a greater speed] because it is higher-pitched and therefore has

> a higher frequency. It thus generates more vibrations per second.' (Electronics student using a hybridisation of the scientifically accepted model and the 'travelling sound particles' model.)
>
> 'The sound of the small bell has a higher frequency than the sound of the large one. It therefore lets the air particles vibrate sooner, that is, faster.' (Telecommunications student using the scientifically accepted model, except with solids, for which he used the 'transmission of sound particles' model.)

In contrast, the remaining three students attributed higher speed to the lower-pitched sound of the large bell, linking the supposedly higher speed to the greater 'sound power':

> 'Although the small bell's sound has a higher frequency, the large bell's sound is more powerful and is thus able to cover the distance more quickly.' (Telecommunications student using the scientifically accepted model, except for one inconsistency.)

Question Q13: Dependence of the Speed of Sound on Intensity

A large majority of the students (over three-fourths) claimed, in a scientifically acceptable way, that the speed of sound does not depend on intensity. However, two of these answers additionally stated that, in contrast, the speed of sound does depend on frequency (the higher the frequency, the greater the speed), which was consistent with their respective answers to Question Q12. For example:

> '[…] The speed will depend on the pitch of each person's voice.'

The remaining four students linked higher intensity to higher speed. For example:

> '[A higher speed,] because [the voice of the person shouting louder] has more intensity, more force.' (Electronics student using a hybridisation of the scientifically accepted model and, mainly, the 'transmission of sound particles' model.)
>
> 'The voice of the person shouting will move the sound particles more quickly.' (Mechanics student using a hybridisation of the 'travelling air molecules' and 'travelling sound particles' models.)

As in the preceding question, Table 2 shows that there is a better qualitative correspondence between the acceptable answers to this question Q13 and the expression of the scientifically accepted model in Questions Q1–Q5 than for Questions Q7–Q11.

Discussion

The Issue of Students' Mental-Model Consistency

The first salient feature of all our results was the (in)consistency in the mental models of sound applied (Results—Questions Q1–Q5). This result is in keeping with other published results (see in particular Hrepic 2004). Hrepic analyses this issue in detail (the level of mental-model inconsistency does not decrease even when an open-ended questionnaire is replaced by a strictly multiple-choice one). His research also proves that most students do not have a clear mental model from the very start, even (in general) after instruction. As a typical feature of prior ideas, it is clear that 'what students normally [bring] into the classroom where sound is concerned (as well as many other physics and scientific topics) is a vast everyday experience and a set of vague ideas and fractioned pieces of knowledge'. According to our students' expressions, this is also an essential reason for the misconceptions observed in our study. Therefore, our research must aim 'to identify those pieces of students' knowledge before instruction in order to build on them, so that students achieve a stable scientifically accepted understanding'. The results reported here should be interpreted from this point of view. This section will also explore some analytical ideas by other authors regarding this phenomenon.

The cases of inconsistency in the model of sound applied by individual students in Questions Q6–Q14 and in Questions Q1–Q5 were especially significant. Even students who had initially used the scientifically accepted model with no inconsistencies at all suddenly attributed supposed object-like properties to sound, claiming, for example, that 'the greater the intensity, the greater the frequency' (questions about frequency), 'the speed of sound is higher when moving in the same direction as the sound source' (Q11) or 'the greater the frequency or intensity, the greater the speed' (Q12 and Q13). This failure to apply the theoretically known wave model shows that these students have not internalised it from a constructivist point of view, this being the essential reason for the mental-model inconsistencies observed.

Qualitatively, this fact can clearly be seen in Table 1 when viewed in combination with Table 2. Table 1, which shows the answers about the mental model of sound, gradually and somewhat regularly 'hollows out' as it moves down, reflecting how it was made, since students were ordered by the number of deviations from the scientifically accepted model. In contrast, in Table 2, which shows the answers to the rest of the questions, large gaps can already be seen in the upper half of the table, along with considerable repetition of the most frequent misconceptions (yellow background).

Eshach and Schwartz (2006, pp. 756 ff.) also observed this mental-model inconsistency in middle school students in ideas about several object-like aspects of sound. They distinguished between 'local coherency' in a specific scenario and 'global coherency': the students they studied were satisfied with the former and did not worry much about the latter. The conclusion would be a conception of sound that is much closer to what diSessa (1988, 1993) long ago described as a 'loosely connected, fragmented collection of ideas' ('Knowledge in Pieces').

Likewise, Wittmann et al. (2003) report a very high degree of inconsistency between the mental models applied to different sound properties by first-year engineering students. They offer an in-depth analysis that considers the reasoning resources used by students in each context. The considerable persistence of mental-model inconsistencies even after instruction is especially remarkable.

Nevertheless, as stated in "Results—Questions Q1–Q5…", our results reveal an increasing degree of consistency in applying the same mental model of sound to the different scenarios when the answers of students following curricula less related to waves (e.g. computing or chemistry) are compared with those of students following the opposite type of curricula (e.g. telecommunications or electronics). Albeit at another level, this finding is paralleled by that of Mazens and Lautrey (2003) in children: the conceptual change in knowledge about sound does not happen through the sudden transfer from one ontological category to another, but rather through a slow and gradual process of belief revision. In other words, one does not go from one fully consistent model to another equally consistent one (i.e. the scientifically accepted one). These authors moreover revise the aforementioned opinion expressed by diSessa (1993), finding a hierarchical order in the loosely connected collection of prior ideas. Regardless, as seen in the "Results" section (Table 2 included), no univocal correlation can be established between degree programmes that deal more heavily with waves, such as telecommunications, and fewer misconceptions about sound, although in our study students of engineering programmes less closely related to waves did hold the most misconceptions. That said, a qualitative trend can indeed be seen.

Basic Mental Model of Sound

Students' mental model of sound is the basis for, and thus the most important element of, both their in-depth understanding of and their ability to interpret acoustic phenomena. Based on the overall results obtained (Section "Results—Questions Q1–Q5…"), the following can be seen:

a. Third-year and fifth-year students applied the scientifically accepted model of sound to most scenarios in Questions Q1–Q5 (about three-fourths of students); however,
b. there were many model inconsistencies (about two-thirds of these students had at least one significant model inconsistency, i.e. only about one-fourth of all students studied were fully consistent). (This is in keeping with the observations in the previous section.)

These results differ considerably from those obtained by Hrepic (2004), even if we look only at the university level. When making this comparison, we must bear in mind that the questionnaire used by Hrepic was different on the whole and was primarily aimed at exploring the details of the mental models and submodels of sound used by students at three different education levels (primary, secondary and tertiary). Moreover, in the statistical treatment of his results, Hrepic included one model (the ear-born model) as different from the other models of sound propagation (wave, intrinsic, dependent, and independent extrinsic models), although he explicitly stated that the difference was not physical (i.e. related to sound propagation), but rather based on language or definition: 'The ear-born sound model is different from the other four in that it is not a mechanism of the propagation, but rather a definition of what the sound is [and it] can be associated with more than one nature of propagation.' Consequently, his results are not directly comparable to ours and this is the possible reason for the discrepancy. Nevertheless, under similar circumstances to those of our study, Hrepic found very low percentages for the wave model (of the order of only 10%, including submodels, scientifically accepted or otherwise) and thus very high percentages for the remaining models, none of which is scientifically acceptable. Furthermore, he observed a lower level of consistency than we did. That said, as noted above, consistency can lead to surprises when one tries to extend it to other questions indirectly related to the model of sound.

Our results are closer to those obtained by Wittmann et al. (2003) for second-semester engineering students. As a relevant reason for the misconceptions which can also be applied to our sample, they found that more than half of the students map object-like properties onto sound waves and do not correctly interpret the event-like properties that are more appropriate in this setting.

Although we were interested in the quantitative aspects only secondarily, our results are also more in line with those of Chang et al. (2007), who found a scientifically accepted macroscopic model of sound transmission in a solid wall in 58% of primary school pupils. Houle and Barnett (2008) found similar percentages in 11- to 14-year-old children (53 and 42% before and after instruction).

Mazens and Lautrey (2003) had previously found percentages for an immaterial conception of sound (‘no substantiality, no permanence and no weight’), which gradually rose from 9% at the age of 6 to up to 50% at the age of 10. However, because of its characteristics (exclusively macroscopic level of sound transmission and education level), this research is only marginally comparable to ours.

In a quantitative study by the authors (Periago et al. 2009) with first-year engineering students, 63% of the individual answers adhered to the scientifically accepted model of sound. However, consistent use of the model in all three proposed questions was as low as 35% (when sound propagation in a wall, the most problematic case, was included). This finding is also in keeping with our results. That study used an abridged and simplified version of the questionnaire used here and was primarily focused on the mental model of sound in three scenarios: sound generation and sound propagation in air and in a wall.

The main misconception associated with the mental model of sound was the notion of sound propagation by means of the travelling of, expressly, air particles or molecules (19% of all 158 valid individual answers to Questions Q1–Q4 in our study compared to 9% in which ‘sound particles’ were involved). This was also the main misconception in the aforementioned study (Periago et al. 2009); there, percentages ranged from about 9 to 45%, depending on the scenario.

Prior ideas Regarding Sound Properties Related to the Mental Model

The Greater the Intensity, the Higher the Frequency

A small number of our students (about one-fourth) failed to give the scientifically acceptable answer to Questions Q6 and Q14 regarding the relationship between pitch and vibration frequency (Section “Results—Questions Q6 and Q14…”). Instead, they linked pitch to intensity and intensity to a higher frequency. This prior idea linking frequency to intensity was also apparent in other scenarios, such as in “Results—Question Q7…” (frequency of sound as dependent on distance travelled). (In that case, the remaining scientifically acceptable answers were based on a different prior idea that attributes object-like properties to sound.) In particular, for the direct question (Q8) on the relationship between intensity and frequency (Section “Results—Question Q8…”), about one-third of the students linked the two parameters, usually claiming that the greater the intensity, the higher the frequency. This same prior idea could also be seen in the scenario in which the sound must go through a solid wall (Section “Results—Question Q10…”), due to the resulting change in intensity. Furthermore, this misconception was generally found to be consistent here with the other scenarios.

We have only seen this misconception reported in the research by Kelly and Chen (1999) in another context, although that study did not clearly quantify how common it was among the population (secondary school students), as it had a different aim. Nevertheless, in two out of 16 preservice and inservice teachers interviewed, Menchen and Thompson (2003) observed possible confusion between pitch or frequency and volume or intensity, as well as the idea that the distance travelled by the sound affects its pitch (resulting in a lower pitch).

In only two students, we observed the opposite misconception, i.e. ‘the greater the intensity, the lower the frequency’. In our opinion, their words (Section “Results—Question Q8…”) suggest a preconception analogous to that regarding pendulum motion reported by Chu et al. (2008) for first-year students in an undergraduate physics course with a poor background in oscillatory motion and waves.

Sound Speed in Air Versus in Solids

A significant number of students (about one-third) said that sound speed is the same in air as in a solid. This result is in keeping with the observation by West (2008), who did not give quantitative rates, in reference to her own research at the non-university level that ‘pupils often entertain the idea that the sound moves at a constant speed regardless of the medium’.

On the other hand, about one-fourth of the students said that sound speed is slower in a solid, reflecting interesting prior ideas involving an object-like conception of sound (Section “Results—Question Q9…”), wherein the solid is perceived as an obstacle that the sound must overcome at the cost of losing speed. Hrepic (1999) found this same conception in all eight of the college students in his study. In contrast, in the same paper Hrepic found that half (four out of eight) of the same sample claimed that ‘the denser the medium, the faster sound propagates’. (Hrepic then went on to analyse this mental-model inconsistency.)

Sound Speed—Variable or Constant?

We have studied some of the prior ideas held by our students regarding the speed of sound in a single medium, which, according to the scientifically accepted model of sound, is always constant.

Sound Speed as Dependent on the Speed of the Source (Section “Results—Question Q11…”) About half of the students claimed that the sound speed was greater when the sound moved in the same direction as the source, thereby seeming to attribute object-like properties to sound. Here again we find a remarkable case of one student (of industrial electricity) who suggests such object-like properties despite having previously used the scientifically accepted model with absolute consistency in the questions directly related to it.

By way of comparison, of the eight college students considered by Hrepic (1999), five (i.e. about two-thirds) claimed that the speed of sound depends on the movement of the sound source (most of them implying that the speed of sound increases in the direction in which the source moves). This percentage was virtually the same (62%) for the full population considered by the author (elementary school, high school and college).

Sound Speed as Dependent on Frequency (Section "Results—Question Q12…") A significant number of students (about one-third) attributed a higher speed to a higher pitch based on reasoning that suggests object-like properties of sound. In contrast, two of all 40 students linked higher speed to a lower pitch, based on the assumption that a lower pitch is more intense. This is in keeping with Case C below.

West (2008) notices that this idea was already held by the Greek philosopher Archytas (ca. 370 BC). Wittmann et al. (2003, pp. 998, 1002) give two highly illustrative examples of the hybridisation of event-like and object-like properties leading to an association of a higher sound speed with higher frequency (second-semester engineering students). Hrepic (1999) likewise found this idea in two of the eight students in his study (i.e. about one-fourth of the population); the percentage rises to 47% if the whole population is included (from elementary school to college).

Sound as Dependent on Intensity (Section "Results—Question Q13…") Here, too, a significant number of students (about one-third) attributed higher speed to a louder sound, once again because they attributed object-like properties to sound.

This proportion is higher than that reported by Hrepic (1999), who found it in only one of the six college students considered in his research. The percentage for the whole population in his paper (from elementary school to college) was 36%, i.e. similar to our result.

Although West (2008) does not give any numerical data about the extent to which this prior idea is held by university students, she notes in a reference to her own research that it is quite common among both younger and older pupils and students and that it can be found throughout the history of science (e.g. in Greek philosophers Plato, ca. 400 BC, and Aristotle, ca. 350 BC). Wittmann et al. (2003, p. 1000) also report a clear example of the application of object-like properties leading to the attribution of higher speed to a louder sound.

Conclusions

In accordance with the stated objectives, the results can be summarised in the following conclusions:

a. Among the students participating in the study, the main misconception in the mental model of sound was the notion that sound is propagated by travelling air particles or molecules. This model misconception was much more frequent than the other misconceived models based on 'sound particles'.
b. About half of these students answered most of the questions directly relating to the mental model of sound in a scientifically acceptable way; however, only about half of this group (i.e. about one-fourth of all students) did so in a way that was completely consistent with a single model. (The fractions provided are merely estimates intended for use as guidelines, with no claim to statistical accuracy, since, as stated above, our main objective was not quantitative.)
c. A trend can be seen in the degree to which model inconsistencies and misconceptions appear in the mental models of sound, depending on which engineering programme a student was pursuing. This trend runs from a lower degree of model inconsistencies and misconceptions for branches such as telecommunications and electronics (the curricula for which include considerable content on waves and the students of which revealed relatively few misconceptions) to a higher one for branches such as computing, chemistry, etc. (just the opposite).
d. Nevertheless, even in students of, for example, telecommunications or electronics, we found many inconsistencies in the application of the event-like model of sound not only to the different specifically proposed contexts or scenarios (about half the students with the mentioned model), but also to the relationships between frequency (or pitch), intensity, the propagation medium, speed, etc. In these cases, students still held misconceptions common at lower education levels, in keeping with the results reported in much of the literature.
e. The main misconceptions regarding the relationships between frequency (or pitch), intensity, the propagation medium, speed, etc., quite often clearly inconsistent with the individual's prevailing model of sound, were as follows:
    - That greater sound intensity is linked to higher frequency.
    - That sound travels at the same speed in air as in solids.
    - That the speed of sound is greater in the direction in which the source of the sound is moving.

- That the higher the frequency, the greater the speed.
- That the greater the intensity, the greater the speed.

Recommendation for Practice and Future Studies

Students do not think about physics consistently, even after additional instruction according to other authors referred to in the Discussion above such as Wittmann et al. (2003) and Hrepic (2004) and also according to our findings of a remaining model-inconsistency even in senior students of more wave-related engineering programmes). These results raise issues for both instruction, in terms of which teaching methods can best help students move towards consistent use of the appropriate physics, and research, in terms of identifying models of student reasoning and finding appropriate learning models.

Nevertheless, the inconsistent mixture of mental models, or the inconsistent application thereof to the different aspects of sound, may turn out to be a 'valuable weak point' that allows the problem to be successfully tackled, providing it can be used to confront students with their inconsistencies and help bring out their uncertainty regarding the coherence of their views. Indeed, as Kirch (2010) confirms, the mediated action of identifying and resolving an emerging uncertainty is an essential process in knowledge generation, which takes place in scientific research and elementary school classrooms alike. This also implies the need for coherent science programmes with a consistent curricular structure based on conceptual schemes instead of curricular conglomerates based on a mix-and-match array of activities that lack conceptual coherence (Bybee 2003).

The 'tutorial' model (that is, the more general theoretical approach rather than the specific materials created) described by Wittmann et al. (2003), with its proven results, including the considerable (although not absolute!) improvement in consistency, may be quite useful, if used to encourage students to reason based on resources. Another alternative would be to use analogies between sound and other wave types as bridging analogies (in the form of blended representations) in traditional classes, given the high (although, once again, incomplete) efficiency reported by Podolefsky and Finkelstein (2007). Positive results have also been reported by Çalik et al. (2010a) for a constructivist-based teaching strategy that includes eliciting and challenging students' pre-existing alternative conceptions. A combination of different methods for bringing about conceptual change has proved to be the most effective way of eliminating such alternative conceptions, specifically with regard to sound propagation (Çalik et al. 2010b). However, a long-term strategy is needed, since, while short-term interventions, even using a mix of constructivist approaches, may produce some degree of knowledge gain, misconceptions prove to be very resistant to consistency and conceptual change (Groves and Pugh 2002).

Correcting misconceptions before they 'harden' by engaging students in discussions of their work in 'help-desk' visits to the teacher is an important part of the learning system proposed by Tribus (2005) for future engineering education.

One approach to the application of the foregoing ideas, which, of course, can always be improved, can be found in the materials for a web-based course on acoustics (Pejuan et al. 2008; Pejuan 2009). Specifically, bridging analogies are applied from the start in the form of blended representations (e.g. a graphic and mathematical description of simple harmonic motion and sound wave propagation), and the course's practical activities consist of materials for ongoing assessment. Also, several laboratory activities, which can even be carried out at home with the own PC, are hands-on activities that help learners confront their uncertainties regarding their model of sound. In future, their effectiveness should be studied in terms of consistency gains in the use of the scientifically accepted model of sound.

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