The Problem of Inconsistency in Reasoning in Engineering Education – A Case Study about the Mental Model of Sound

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Abstract

Every planning of an efficient teaching has the aim of achieving satisfactory learning outcomes. From a constructivistic point of view, it is a commonly accepted fact that such a planning has to take into account the prior ideas that students bring to the class. In order to know them, we carried out a survey about the prior ideas on the nature of sound that our fifteen third-year engineering students had at the begin of an elective subject on acoustics. We used a questionnaire where the students had to express their prior ideas with their own words. Although the students expressed scientifically accepted ideas in about 2/3 of the individual questions on a whole, a cross comparison between each student's answers for the different scenarios revealed a great number of inconsistencies in the mental model of the nature of sound (wave model): only about 1/3 of our students were consistent in all these scenarios. The inconsistency in their reasoning was still clearer when each student had to apply his/her respective mental model about sound to several properties of sound, in particular the relationship between pitch and distance travelled by sound. We analyse the state of the art in the literature about the issue of students' consistency, and we consider some proposals suggested in the literature, which we apply in part in our own teaching resources, in order to overcome this inconsistency problem.

Keywords: inconsistency, prior ideas, mental models, acoustics.

1. Introduction

Every planning of an efficient teaching has the aim of achieving satisfactory learning outcomes. From the point of view of a constructivist teaching, there is remarkable consensus about the need to have a detailed image of the students' or pupils' previous understanding of the physical phenomena before their formal study, when planning and implementing learning activities. 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 call prior ideas or misconceptions, are not consistent with scientific conceptions (Linder and Erickson, 1989; Wittmann et al., 2003; Chang et al., 2007).

This is also important in order to avoid the traps that the traditional teaching resources may become, like those graphs, illustrations and texts that pose risks of reinforcing prior ideas which are not scientifically accepted (Leite and

Afonso, 2001; Wittmann et al., 2003). Also when using analogies, as resorting to water waves to explain the sound waves, one has to bear in mind their important limitations and ‘traps’, in spite of the often proved scientific and didactic value of analogies (Podolefski and Finkelstein, 2006, 2007). They will be productive only if applied as ‘bridging analogies’, choosing a bridging strategy that builds on students’ prior conceptions and bearing in mind the many ways how the representations can be interpreted, so that one can create a conceptual blending between productive representations.

Misconceptions about sound have been quite widely investigated in primary and secondary education (e.g. Eshach and Schwartz, 2006; Chang et al., 2007), but only scarcely in engineering education (e.g. Hrepic, 2004). Some of the co-authors have previously investigated the prior ideas in other fields of physics at this level of engineering education (Periago and Bohigas, 2005).

Misconceptions about sound are expressed in scientifically unaccepted mental models about the nature of sound, as well as in partial aspects of sound to which students are expected to apply their mental models. An important item in this context is the students’ inconsistencies in reasoning found in virtually all the quantitative research about prior ideas, also at university level.

The specific objective of this research was to verify in which way (qualitative aspect) and, only secondarily, to which extent (quantitative aspect) the mentioned misconceptions and inconsistencies are given in a group of engineering students.

2. Experimental aspects

2.1. The sample

The sample consisted of 15 third-year university students from different engineering branches, i.e. different curricula, who were going to study an elective subject on acoustics. Within their secondary education and also within the subject of first-year engineering physics, their curricula include simple harmonic motion and waves in general. Additionally, depending on the engineering branch chosen, some of them, for example those of telecommunication, have received a wider instruction on the aspects of sound which are more related to the that specific engineering branch. In other branches, as in industrial mechanics, sound is virtually not further present in the curriculum.

As for the limited extent of this sample, one has to take into account the rather qualitative nature of this research. We rather wanted to capture the richness of the students’ responses and their relationship to the respective engineering curricula, also by cross-comparison between the different answers from each student. This was here more interesting for us than the exact percentages of students that expressed a prior idea or another one.

Our research assumes as a starting point that, at this university level, the student has already ‘learnt’ that sound consists of vibrations, although we bear in mind the possibility that in practice, this idea may be so confused in the student’s mind, that it is not more than a concept memorized but not assimilated as for its physical meaning. A logical result is the inconsistency in applying this idea as the essential part of his/her model of sound.

2.2. The questionnaire

For this research, a questionnaire was used which combined half closed-ended (multiple-choice) and, especially, open-ended questions. For the latter, each student had to write an explanation using his/her model of sound with his/her own words. This matches the technique followed by Hrepic (1998) or that with two-tier questionnaires (Chang et al. 2007), since in these studies and also in others (e.g. Hrepic et al. 2003 and Hrepic 2004) this method has proved to provide concrete and useful information.

When distributing the questionnaire to the students, it was stressed that its target was to improve the learning activities of the subject and in no case it would be graded whether the answers were academically acceptable or not. As a stimulus to fill the questionnaire, only a small bonus was added to the mark just for filling it in the established time, before going into the subject.

The main questions (Q1 to Q5) addressed directly the student's mental model of sound at microscopic level, in different scenarios: production, transmission in air, solids and through a solid wall, as well as perception in the ear. As for delimiting concrete mental models proposed, we used the conclusions by Linder and Erickson (1989) (basic models and model hybridisations), Hrepic et al. (2003) and Hrepic (2004).

So, the four different models proposed here correspond essentially to those proposed by Hrepic (2004) (questions Q1 to Q4) and in part by Chang et al. (2007) (question Q5), from whom we take the questions almost literally. This allow a comparison of our results with those from the literature, when they exist, in spite of the possible difference of education level. Following the same order as in their graphic schematic representation in Figure 1, they are the following:

A) Vibration of air or propagation medium molecules, which is propagated to the neighbouring molecules.
B) Air molecules moving among the other air molecules, or among the propagation medium molecules when they fall on these.
C) Sound particles moving aided by the previous random motion of the air or propagation medium molecules, which transfer the sound particles from one to the next molecule.
D) Sound particles with a motion among the air or propagation medium particles, which then, as a result, vibrate.

As an example of these five first questions, Figure 1 shows Question 2 (scenario: sound propagation in air).

[Insert Figure 1 about here]

Other open-ended questions, for example the one with number Q7, addressed the prior ideas concerning different aspects of sound, like the dependence of sound frequency on the distance travelled by sound:

> (Q7): A drum is given a hit, so that it vibrates. Let us assume that its membrane makes 80 vibrations per second (a fairly realistic value). When the sound from the drum reaches our ear through the air, it makes the eardrum vibrate. Please state whether the amount of vibrations per second increases, diminishes or remains the same depending on the distance between drum and ear. Please explain your answer.

3. Results

Figure 2 is a synopsis of the results obtained. The rows for the different students have been arranged (approximately) by degree of scientific acceptability for the different aspects of the model of sound. The fields give the categorization of the answers to the different questions. They have a green background if the answer fits the scientifically accepted model of sound. The majority answers (or majority answer categories) which do not fit this model have a yellow background.

[Insert Figure 2 about here]

3.1. Mental models of the nature of sound (questions Q1 to Q5)

From the fifteen students of the group, only four expressed the scientifically accepted model with no inconsistency. These are two students of telecommunication (speciality 'Sound and Image'), one of industrial electronics and one of industrial electricity.

Ten further students hybridize the scientifically accepted model (Model A of Subsection 2.2) with other models, leading to different inconsistencies (one to two inconsistencies).

The widest deviation from this Model A is shown by the two last students of aeronautics and mechanics, who do not use this model in virtually any of the scenarios (at least in a clear way), but they express almost consistently another model (Model B, movement of air molecules).

If all 45 different individual answers for the different scenarios proposed in open-ended or half open-ended questions are analysed, 29 of them (i.e. about 2/3) express the scientifically accepted Model A. From the remainder, 9 (i.e. about 1/5) express the Model B (movement of air molecules) and the other 7 (less than 1/6) let 'sound particles' take part in different ways (Models C and D).

Some expressions in these students' answers (Question Q3, scenario: sound perception in the ear):

> 'I think that the air or sound particles collide with the eardrum at a given speed; this speed makes the sound to be more or less pronounced' (answer categorized as Model B, movement of air particles, since this mechanics student also used this model in other scenarios).

> ‘The vibrating air particles pass through the particles of the ear membrane [eardrum], which is the vibration that the nervous cells receive […]’

3.4. Relationship between frequency and travelled distance (Question Q7)

Only five of the 15 students gave a scientifically acceptable answer. Two of these five students (a telecommunication student and an industrial electronics student) hat applied the scientifically accepted model of sound (questions Q1 to Q5) in a fully consistent way (i.e. to all scenarios). But in the opposite side, one of these students (an aeronautics student) is the one that had consistently used one scientifically unacceptable model (‘movement of air particles’) in virtually all scenarios.

As for the example of question about the relationship between frequency and distance travelled, we would point out the following ones:

> ‘[The vibrations per second] increase because they must reach the brain’ (electronics student; model of sound scientifically accepted with only one clear 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 there is a part of the vibration energy that gets lost, so that the sound will arrive with a different number of vibrations depending on how far away you are’ (telecommunication student, with a scientifically accepted model of sound with no inconsistencies until now!).

This answer is 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, also with the scientifically accepted model of sound with no inconsistencies until now!).

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.

Seven more students also linked frequency to intensity, which decreases with distance. One of them (a telecommunication student, with an inconsistent hybridization 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.

Summing up, there is a remarkable frequent association between distance and intensity (scientifically accepted) and between intensity and frequency, understood as the number of vibrations per second, in addition to ideas resulting from an at least partially object-like conception of sound.

It is also remarkable that there are students who had previously expressed the scientifically accepted model, some without any inconsistencies, and now express ideas linked to an object-like conception of sound.

4. Discussion

4.1. The issue of students' consistency

The first point that attracts attention in all our results is the fact of the (in)consistency with regard to the applied mental model of sound (Section 3.1). This result agrees with other research results published (see specially Hrepic, 2004). Hrepic analyzes this issue in detail (the inconsistency level does not decrease even when going from an open-ended version to a pure multiple-choice questionnaire). His research proves also that the most students do not have a clear mental model from the very beginning, even (in general) after instruction. Here it can be clearly seen, as a typical feature of prior ideas, 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'. Therefore, the aim of our research must be 'to identify those pieces of students' knowledge before the instruction in order to build on them, so that students achieve stable scientifically-accepted understanding'. It is from this point of view that the results reported in this paper should be interpreted.

The inconsistency cases in Question Q7 with regard to the model of sound according to Questions Q1-Q5 in each student are specially significant. Even students who had expressed the scientifically accepted model at first, with no inconsistency at all, now attribute supposed object-like properties to sound, such as 'the greater the intensity, the higher the frequency'. This failure to apply the wave model allegedly known shows that these students have not internalized it from a constructivistic point of view. In this section, we will see some analytical ideas by other authors about this phenomenon.

Eshach and Schwartz (2006, pp. 756 ff.) also observed this inconsistency in middle school students, in ideas about several object-like aspects of sound. They distinguish the 'local coherency' in a specific scenario from the 'global coherency': they are already satisfied with the former and do not worry very much about the latter. The conclusion would be a conception of sound which is much closer to what diSessa (1993) expressed long ago as a 'loosely connected, fragmented collection of ideas' ('Knowledge in Pieces').

Also the paper by Wittmann et al. (2003) reports a very high degree of inconsistency between the mental models applied to the different sound properties at the first-year level of engineering education. It contains a deep analysis considering the reasoning resources applied by students in each context. The fact of the considerable inconsistency persistence even after instruction is especially remarkable.

Nevertheless, in our results we ascertain a progressive prevalence of the scientifically accepted model with a progressively increasing degree of consistency if we compare the answers from students with curricula less related to waves (extreme case: mechanics) with the ones from students with the opposite type of curricula (example: telecommunication). Although at another level, this ascertainment has a parallel in that by Mazens and Lautrey (2003) for children: the conceptual change in knowledge about sound does not happen through the sudden transfer from an ontological category to another, but rather through a slow and gradual process of belief revision. In other words, one does not goes from a model which is consistent in all its details to another model (the scientifically accepted one) which is also consistent in all its details. By the way, these authors revise diSessa's (1993) point of view mentioned before, since they find a hierarchical order in the loosely connected collection of prior ideas.

Anyway, the results of the preceding section 3 show that no univocal correlation can be established between the degrees which are more related to waves (like telecommunication) and a lesser absence of misconceptions about sound, although our case of mechanics has the highest number of misconceptions. But indeed, we do find a trend of qualitative nature.

4.2. Basic mental model of sound

The student's mental model is the basis and therefore the most important element to understand the acoustical phenomena in depth and to be able to interpret them. From the obtained results on the whole (section 3.1), we have seen the following:

(a) The model of sound applied by third-year students to most scenarios of Questions Q1-Q5 is the scientifically accepted one (about 2/3 of individual cases), but:

(b) with an important number of inconsistencies (only about 1/3 are fully consistent, i.e. about 2/3 have at least one relevant inconsistency) (expression of the comment in the previous section).

These results differ remarkably from those obtained by Hrepic (2004), even if we keep to the university level. For a comparison, we must bear in mind that this author uses a questionnaire which is different on the whole, with objectives focused rather on the details of mental models and submodels of sound in students of three different levels (primary, secondary and tertiary education). Besides, in the statistical treatment of his results, Hrepic includes a model (ear-born model) as different from the remaining models of sound propagation (wave, intrinsic, dependent, and independent extrinsic model), although he explicitly admits that the difference is not of physical type (of sound propagation), but rather of linguistic or dictionary concept: '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 can be associated with more than one nature of propagation.' This causes that his and our results are not directly comparable. Nevertheless, under similar circumstances to those of our research, Hrepic finds very low percentages for the wave model (on the order of only 10%, adding submodels, either scientifically accepted or not) and thus very high percentages for the remaining models, scientifically not accepted. Also the consistency level which he observes is lower than ours, but, as already commented, consistency can spring surprises when one tries to spread it to other questions indirectly related to the model of sound.

Our results are nearer to those obtained by Wittmann et al. (2003) in engineering students in the second semester, where, as a summary, more than one-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.

Our results are also more in line with those by Chang et al. (2007). These authors find a scientifically accepted macroscopic model of sound transmission in a solid wall in 58% of primary school pupils. Mazens and Lautrey (2003) had found before percentages for an immaterial conception of sound (‘no substantiality, no permanence and no weight’) which rises gradually from 9% at the age of 6 up to 50% at the age of 10. Nevertheless, because of their characteristics (exclusively macroscopic level of sound transmission, and education level), this research is comparable to ours only to a limited extent.

In another paper by the authors (Periago et al., 2009), the individual answers matching the scientifically accepted model of sound make 63%, but also here the consistency for this model in all three proposed questions gets down to about 35% (including the most conflictive case, sound propagation in a wall), also in line with our results. This paper is a rather quantitative study in 65 first-year engineering students with a reduced and simplified version of the same questionnaire as ours. Essentially, this study is limited to the mental model of sound in three scenarios: sound generation and sound propagation in air and in a wall.

4.3. Application of the mental model to a given case: relationship between sound frequency and distance travelled

The prior idea linking frequency to intensity emerged in the answers to several questions. One of these questions was Q7, since intensity decreases with the distance travelled. The answers to this question reveal a great number of inconsistencies when applying the mental model of sound previously stated, as shown in Figure 2.

We have found this misconception reported only in the research by Kelly and Chen (1999) in other contexts, although without a clear quantification of its incidence in the investigated population (secondary education), since the objective of this research was another one. Nevertheless, in 2 preservice and inservice teachers out of 16 interviewed, Menchen and Thompson (2003) verify the possible confusion between pitch or frequency and volume or intensity and that the distance travelled by the sound affects the pitch (resulting in a lower pitch).

5. Conclusions

In accordance with the objective established at the beginning, the results obtained can be summarized in following conclusions:

a) About 2/3 of the third-year students which were the object of study answer in a scientifically acceptable way to most considered questions directly referred to the mental model of sound, but only 1/3 do this in a way which is completely consistent with one model.
b) Although the preceding quantitative aspect was not our main objective, a trend is indeed observed in the degree to which the inconsistencies and misconceptions appear in the mental model of sound, depending on the engineering programme of our third-year students. This trend goes from branches like e.g. telecommunication (high presence of contents on waves in the curriculum; relatively few misconceptions) up to branches like e.g. mechanics (opposite case).
c) Nevertheless, even in students e.g. of telecommunication or electronics, we find many inconsistencies (in about 2/3 of all cases) when applying the wave-like model of sound not only to the different scenarios specifically planed, but also to aspects like the relationship between frequency (or pitch) and the distance travelled by sound. In these cases, they still have typical misconceptions for lower educations levels, in good agreement with many results reported in the literature.

6. Further steps

Students do not think about physics consistently (even after additional instruction). These results raise issues both for research, in terms of models of student reasoning and appropriate models of learning, and also for instruction, in terms of which teaching methods can best help students move toward consistent use of the appropriate physics.

Nevertheless, the inconsistent mixture of mental models or their inconsistent application to the different aspects of sound can be the typical ‘valuable weak point’ which allows to attack the problem successfully, if we are capable of taking advantage of it to confront the student with his/her inconsistencies and let him/her arrive on his/her own to a consistent and scientifically accepted model of sound. Thus, the model of ‘tutorial’ (the more general theoretical approach rather than the specific materials created) described by Wittmann et al. (2003) can be very useful, with its proven results, including the remarkable (but not absolute!) consistency improvement, making use of a students’ reasoning based on resources. A further alternative is the application of analogies between sound and other wave types as bridging analogies (in form of blended representations) within the traditional class, with the high (but neither here absolute) efficiency reported by Podolefsky and Finkelstein (2007). Also the ongoing assessment as described by Treagust et al. (2001) for middle school pupils (with the incorporation of assessment practices embedded in instruction) seems to provide an effective technique to change the scientifically not acceptable conceptions specifically about sound.

An approach to the application of these ideas, which, of course, can always be improved, lies in the materials for a web-based course on acoustics (Pejuan et al., 2008; Pejuan, 2009). In particular, from the very beginning bridging analogies are applied in form of blended representations (graphic and mathematical description of the simple harmonic motion, sound wave propagation of an acoustic), and as for practical activities, the course provides materials for an ongoing assessment. In the future, its effectiveness has to be studied in terms of consistency gains in the use of the scientifically accepted model of sound.

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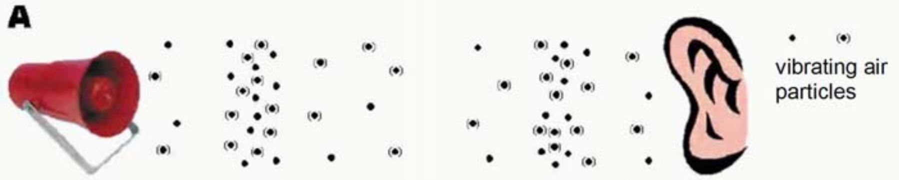
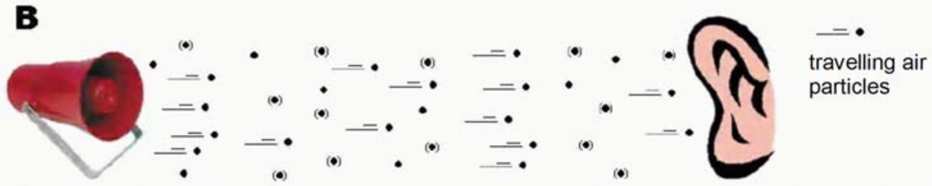
Figure 1 *One of the first five questions (Q2) on mental model of sound (scenario: sound transmission in air) (taken from Hrepic, 2004). The graphic representations correspond to the four basic models mentioned in the text, in the same order.*

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.

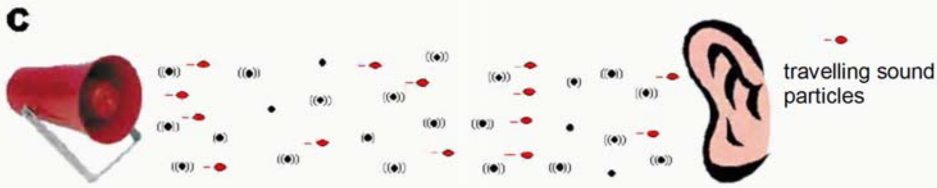
A) Air particles, superposed on their chaotic motion in all directions, start to vibrate when they come into contact with the loudspeaker in the direction from which the sound is propagated (from the loudspeaker to the eardrum). When they come into contact with neighbouring air particles, they also make 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.



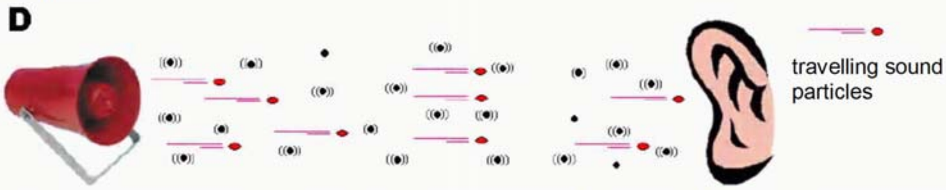
B) The air particles that are in contact with the loudspeaker are transmitted through the other air particles, which carry the sound from the loudspeaker to the ear. As a result, all the other air particles vibrate.



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:

Figure 2 *Overview of the results for the different students enrolled in different engineering programmes.*

	Model of sound					Frequency versus distance travelled	Inconsistencies regarding prevailing model of sound
Scenario (Q1-Q5):	Sound emission	Propagation in air	Sound reception	Propagation in a wall	Propag. in closed container		
Question:	Q1	Q2	Q3	Q4	Q5	Q7	
Students							
Telecomm.	✓	✓	✓	✓	✓	✓	0
Electronics	✓	✓	✓	✓	✓	✓	0
Telecomm.	✓	✓	✓	✓	✓	[3]	1
Electricity	✓	✓	(✓)	✓	✓	[5]	1
Telecomm.	MS/TS	✓	✓	✓	✓	✓	1
Telecomm.	✓	✓	✓	TS	✓	[3]	2
Telecomm.	✓	✓	(✓)	✓	[1]	[3]	2
Electronics	✓	TS	(✓)	✓	[1]	[3]	3
Electronics	✓	MS	✓	✓	[1]	[3]	3
Computing	MA	MA	(✓)	✓	✓	[3]	2
Aeronautics	✓	✓	(✓)	MS	[2]	(✓)	2
Telecomm.	✓	✓	(✓)	TS	[2]	[6]	3
Mechanics	MA	✓	MA/MS	MA	✓	[4]+[7]	3
Aeronautics	MA	MA	(✓)	MA	[1]	✓	(2)
Mechanics	MA	MA	MA	MS	✓	[3]	(3)

MA = Movement of air particles
MS = Movement of sound particles
TS = Transmission of sound particles
[1] Sound never passes through a wall that completely encloses the sound source.
[2] Sound only partially passes through a wall that completely encloses the sound source.
[3] Greater sound intensity is linked to higher frequency.
[4] The higher the frequency, the greater the speed of the sound particles.
[5] Higher frequency at the eardrum due to greater vibration concentration in the space.
[6] Vibration wears out as it travels.
[7] Particles gradually lose speed as they travel.

(In yellow: most frequent misconceptions)

✓ = Clearly according to the scientifically accepted model
(✓) = Compatible with the scientifically accepted model