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Validation of a learning progression for sound propagation in air

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Abstract

This study was conducted with 37 11th grade secondary school students and had as its focus to verify the different levels of sophistication in students' explanations regarding the propagation of sound in air. A pre- and a post-test were conducted after a one-month intervention, focusing on learning about sound propagation in air. Data analysis allowed for comparing the progressions in the sophistication of students' explanations and validating the proposed categorical structure of the hierarchical levels of learning progressions (LPs). The validity was confirmed by the consistency of the category hierarchy, assessed in terms of the difficulty coefficients of LPs levels, which were distinct in the two tests but maintained the established order in the construct maps. In the pre-test, the more sophisticated levels of LPs were not elucidated, but after instruction, in the post-test, there were explanations at all levels. The results also reveal the importance of instruction focused on LPs, so that students can present more sophisticated explanations, and their utility for future investigations using this approach.

Keywords: learning progressions, secondary school, acoustic, sound propagation, science education

INTRODUCTION

Science education is a constantly developing field, which is marked by significant changes in terms of teaching practices and understanding how students explain the different natural phenomena. The research in this field has led to practices that make concepts more accessible to students, focusing not only on the concepts but also on the processes of science (Evagorou et al., 2015). The processes that take place during scientific investigations include, among others, formulating problems, developing and using models, arguing and constructing and communicating explanations about a phenomenon (NRC, 2012). As studies advance in the field of science education, new perspectives emerge on how students develop their scientific knowledge through their explanations.

A scientific explanation can be understood as the way students use to communicate their reasoning about a scientific phenomenon, thus enabling their thinking to be made visible or audible (Braaten & Windschitl, 2011). However, a good scientific explanation must be based on the central ideas of a given content (Gotwals & Songer, 2010). These ideas are the fundamental concepts used to explain different phenomena and are the theoretical basis for understanding a certain scientific field. Central ideas can include fundamental laws, such as Newton's laws of motion in physics, which explain different mechanical phenomena.

A good explanation needs to present a coherent and supported answer to a question, with essential components such as an affirmation, evidence and reasoning. The affirmation is the answer or initial explanation to the problem, the evidence is the examples or data provided to support that affirmation, and the reasoning is the link between the affirmation and the evidence (Gotwals & Songer, 2010; Laliyo et al., 2023; McNeill & Krajcik, 2008).

As well as providing a robust understanding of the key concepts, a good explanation can demonstrate the ability to apply them to different specific phenomena. It does not just list facts, but integrates models,

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Contribution to the literature

- The research validates the hierarchical structure of learning progressions on the propagation of sound in air, confirming the consistency of difficulty levels through Rasch model. It uses probabilistic statistical modelling to validate learning progression levels, contributing a robust and less subjective methodological approach to future research in science education.
- It specifically addresses how students learn about the propagation of sound in air, filling a gap in the literature that has rarely investigated this topic with a focus on learning progressions. It provides a solid basis for future investigations into learning progressions in other science topics, encouraging the continuation and further spread of this type of research.
- The study reinforces the importance of essential components for the elaboration of a good scientific explanation, such as the presence of affirmation, evidence and reasoning; demonstrates how teaching centered on learning progressions can improve both students' ability to integrate these components into their explanations and to present more sophisticated explanations of sound propagation, at different levels of the learning progression. It therefore demonstrates the effectiveness of teaching centered on learning progressions in improving students' understanding of scientific concepts of different complexity.

complementary knowledge and concrete data to build a consistent, coherent and comprehensive narrative (Braaten & Windschitl, 2011; Gotwals & Songer, 2010; Laliyo et al., 2023).

However, studies have also investigated the emergence of alternative conceptions in students' explanations. The idea that students present alternative conceptions when explaining a phenomenon became widely discussed in the late 1970s and especially throughout the 1980s (Taber, 2019).

Since then, several studies have also been dedicated to investigating the alternative conceptions and common errors present in students' explanations. However, the purpose of these studies was to identify such conceptions and analyze how they were addressed in students' explanations (Alonzo & Gotwals, 2012; Alonzo & von Aufschnaiter, 2018; Krajcik, 2012).

In the early 2000s, NRC proposed an approach focused on students' learning progressions (LPs). Progressions seek to understand the pathways through which students' explanations of a particular science topic become more sophisticated after instruction and/or over the course of the school years.

From a perspective that goes beyond verifying alternative conceptions and common errors in students' explanations (Alonzo, 2011; Covitt et al., 2018), these explanations are described in successive and increasingly sophisticated levels based on coherent ideas, previous instruction, and experiences (Duschl et al., 2011; Krajcik, 2012; Smith et al., 2006).

Thus, LPs present a sequence of successive and more complex forms of reasoning about an idea that reasonably reflects how a student learns a particular scientific concept (Alonzo & Steedle, 2008; Jin & Anderson, 2012; Smith et al., 2006).

There have been investigations on LPs in various science topics; however, despite studies that focused on understanding students' alternative conceptions and common errors in the various topics related to the content of Sound (Eshach et al., 2018; Fazio et al., 2008; Hernandez et al., 2012; Hrepic et al., 2010; Sozen & Bolat, 2011; Volfson et al., 2018), research on sound from this perspective is still insipient.

Sound is a relevant curricular topic that is present in students' daily lives and is studied in both primary and secondary schools, and there is a notable lack of studies on how the students' progress in their knowledge of sound. For example, there is no study that attempts to understand how students explain the propagation of sound in the air, from the moment the sound is emitted by a source until it reaches the receiver. With the aim of furthering knowledge in this approach regarding the content of sound, specifically sound propagation in air, this investigation was conducted with 11^{th} grade secondary school students, the last year they study this content. A pre- and a post-test were used, following an intervention that addressed the following topics: the mechanical nature of sound, how sound propagates, how sound affects the air as it propagates, the role of air as a medium of propagation, and why sound does not propagate in a vacuum.

Studies employing LPs approach typically begin with the development of construct maps, which comprise a categorical structure describing the different levels of sophistication for students' explanations on the topic. Probabilistic Rasch modelling is one of the different methods used to validate the established hierarchical levels for the categories, and this can be done by assessing the consistency of the difficulty coefficients (Covitt et al., 2018; Jin et al., 2019; Plummer et al., 2015, 2020; Wilson, 2009).

The main objective of this study is to validate LP on the propagation of sound in air. Based on the construct map drawn up in a previous study, the study is guided by the following research question: *How are the hierarchical levels of LP on the propagation of sound in air described?*

According to the construct map (Costa et al., 2023), the different levels of explanations elucidated from the test responses were analyzed. One-dimensional Rasch modelling is then used to verify

(a) whether the construct map on sound propagation in air presents hierarchical levels of sophistication for students' explanations,

(b) whether the hierarchy of sophistication levels is maintained across different test administration moments, and

(c) whether students' explanations become more sophisticated after instruction focused on LPs.

CONCEPTUAL FRAMEWORK

Learning Progressions in Science Education

LPs seek to understand how students' explanations about a specific science topic become more sophisticated after instruction and/or over the course of the school years. LPs describe, in successive and increasing levels of sophistication (Duschl et al., 2011; Krajcik, 2012; Smith et al., 2006), the explanations given by students, recognizing the progression from lower to higher levels, including the intermediate levels (Alonzo & von Aufschnaiter, 2018; Plummer et al., 2015). LPs present the students explanations about a certain phenomenon (Alonzo & Steedle, 2008), after a teaching sequence or over school years, moving from an embryonic understanding of a scientific concept to a more mature scientific knowledge, free from alternative conceptions and conceptual errors.

One of the most important premises of this approach is the requirement for empirical accounts of how students express their reasoning. One of the most common and recurrent data collection instruments is written tests, which can consist of multiple-choice items or open-ended items (Alonzo & Steedle, 2008; Jin & Anderson, 2012; Jin et al., 2019; Osborne et al., 2016).

For items that are part of the diagnosis of students' reasoning, whether they have received formal instruction on the assessed content or not, their relevance should be verified to elucidate intuitive ideas of both younger students and those who have not received formal instruction on the content. By interpreting the responses, the reasoning patterns used by students can be identified (Jin et al., 2019).

The evidence gleaned from test responses that supports the subsequent development of progression levels in the assessed topic is categorized and organized a priori, following what the literature presents as construct map (Alonzo & Steedle, 2008; Jin et al., 2019; Plummer et al., 2015, 2020; Wilson, 2009).

> "A construct map can be well-thought-out and investigated as an ordering of qualitatively different performance levels focused on an observed characteristic" (Wilson, 2009, p. 718).

Construct maps present the upper level, intermediate levels, and lower level of students' explanations on the assessed topic. The development of the upper level, which refers to the central idea and scientific concepts, can be supported by educational guidelines, student textbooks, and scientific literature. To assess the cognitive and pedagogical aspects and the alignment of the content with the assessed grade level, it is common to consult scientists, science education researchers, and science teachers (Jin et al., 2019).

In studies on LPs, it is assumed that the administration of the items should provide sufficient evidence for classifying the progression levels, including their differentiation, distinctiveness, and ordering (Jin et al., 2019; Wilson, 2009). Various quantitative techniques can be used for this purpose. These techniques aim to analyze students' responses to assessment items, identify performance patterns, and verify whether the items are indeed providing relevant information to differentiate the levels of progressions. Moreover, these techniques also allow for verifying whether the order of the levels is empirically supported through the analysis of students' scores across different levels (Jin et al., 2019).

While traditional sequences often focus on assessing content learning, LPs are concerned with elucidating the paths of knowledge development. That is, they aim to identify how students' reason to explain a particular concept and how that reasoning evolves over the course of the school years or after instruction.

Alternative Conceptions & Common Misconceptions About Sound Propagation

One of the pieces of evidence used to draw up the preliminary construct map is the identification of students' alternative conceptions and common errors that should be considered for LP. In this section, we are concerned with presenting, based on the literature, the possible alternative conceptions that students may have about the content of sound.

The previous ideas and alternative conceptions that students carry with them make it difficult for them to learn meaningfully and permanently, which is why it is important to identify them as soon as possible, helping them to overcome these obstructive factors in their learning (Sozen & Bolat, 2011). One of the difficulties in transposing alternative conceptions into scientific knowledge is that some erroneous or mistaken thoughts have already been materialized by the students (Eshach et al., 2018; Minozzi & Marlozi, 2019) and therefore it is up to the teacher to design appropriate strategies for this transposition to take place.

Table 1. Student´s conceptions about sound propagation & speed

Subject	Conceptions	Studies that refer to conceptions
Sound propagation	Sound is an entity that is carried by individual molecules as they move through the medium.	Eshach et al. (2018), Fazio et al. (2008), Hrepic et al. (2010), & Linder (1992)
	Sound is the propagation of sound particles that are different from the particles in the medium.	Hrepic et al. (2010)
	Sound is a material unit of a substance or has mass.	Hrepic et al. (2010)
	Sound is an entity that is transferred from molecule to molecule through the medium.	Fazio et al. (2008), Hrepic et al. (2010), Linder (1992), & Volfson et al. (2018)
	Sound is propagated by ethereal particles, which can be particles called sound, sound waves, or sound particles.	Hrepic et al. (2010)
	Sound passes through empty spaces between particles in the medium (a property called infiltration).	Hrepic et al. (2010)
	Sound pushes air molecules in the direction of its propagation	Fazio et al. (2008) & Hrepic et al. (2010)
	Sound moves because the air pushes it.	Eshach et al. (2018) & Hrepic et al. (2010)
	In water, the sound particles are pushed by the water molecules.	Eshach et al. (2018)
	Sound is a limited substance with momentum, usually represented in the form of flowing air.	Linder (1992)
	Sound moves like an invisible liquid.	Eshach et al. (2018)
	Sound waves spread through the air and cause the air to spread away from the source.	Fazio et al. (2008)
	Sound is a limited substance in the form of some traveling pattern.	Linder (1992)
	Sound is connected to concept of waves as part of a physical-mathematical modeling system (in this context, cannot be distinguished from light: wave equation would appear identical).	Linder (1992)
	Sound as a transient substance that moves from the source to the listener and can suffer friction.	Hrepic et al. (2010) & Volfson et al. (2018)
	Sound is independent–sound propagates through a vacuum (e.g., it does not need a medium).	Eshach et al (2018), Fazio et al. (2008), & Hrepic et al. (2010)
	Sound propagates only in air.	Fazio et al. (2008)
Sound propagation speed	The variation in wave speed depends on certain characteristics of the wave (amplitude, transverse velocity, or pulse duration).	Fazio et al. (2008)
	The variation in wave speed depends on the properties/characteristics of the medium such as density, temperature, tension, elasticity, etc.	Fazio et al. (2008) & Volfson et al. (2018)
	The speed of sound is greater in denser media (less molecular separation facilitates sound propagation). The speed of sound is lower in denser media (larger or closer molecules make it more difficult for sound to propagate).	Fazio et al. (2008) & Volfson et al. (2018)
	Metal/water obstructs or hinders sound propagation.	Fazio et al. (2008)
	Intense sounds push air faster.	Fazio et al. (2008)
	In water, sound cannot be heard. The reason for this is that water is denser than air, and the water particles therefore collide with the sound particles and destroy their movement.	Eshach et al. (2018)

Understanding and analyzing students' alternative conceptions has also been a concern of studies in the field of science education in recent decades. These studies have revealed that students bring with them concepts and misconceptions, or ideas that still need to be refined scientifically, about the content being studied in the classroom. These conceptions, which are not scientifically correct, sometimes remain with students even after instruction (Sozen & Bolat, 2011).

Consistent with the aim of this study on the content of sound, the literature shows that students carry alternative conceptions related to the propagation of sound and its speed throughout their school years. Most students, before having contact with the content of sound, understand these concepts in a way that does not correspond to a scientific explanation. The earlier the appropriation of erroneous or mistaken concepts about sound takes place, the more difficult it becomes for students to make transposition (Merino, 1998a, 1998b).

The difficulties presented by students during the teaching-learning process need to be identified. The teacher must be the mediator who helps them to modify their spontaneous thoughts, reorganizing them, refining them, and building scientific knowledge (Hrepic et al., 2010; Merino, 1998b).

To develop LP, it is important to understand what the students bring as alternative conceptions, misconceptions, and errors regarding the propagation of sound and the speed of propagation. **Table 1** provides a summary of these conceptions.

In relation to the propagation of sound, some alternative conceptions have been found in previous studies on acoustics. In line with the literature, some students believe that sound is an entity that is carried by individual molecules as they move through the medium (Eshach et al., 2018; Fazio et al., 2008; Hrepic et al., 2010; Linder, 1992). Others think that sound is the propagation of sound particles that are different from the particles in the medium. In addition, some students conceive of sound as a material unit of a substance or that it has mass (Hrepic et al., 2010).

Sozen and Bolat (2011) revealed that some misconceptions are common among students, such as the idea that sound is identified by the ear due to the phenomenon of reflection. Hrepic et al. (2010) point out that, among other alternative conceptions, students believe that sound is a particle that propagates through the air. Nevertheless, it highlights impact of instruction on the development of concepts relating to sound.

The studies thus highlight the importance of identifying and understanding students' alternative conceptions, as they directly influence the teaching-learning process. These conceptions can hinder the assimilation of correct concepts and the development of scientific knowledge about sound. It is therefore essential to address these conceptions explicitly and provide students with opportunities to reconstruct their knowledge. Although alternative conceptions of sound represent a challenge when it comes to teaching this content, through appropriate approaches and the identification and treatment of conceptions, it is possible to help students develop a more precise and coherent knowledge of properties and characteristics of sound.

METHODS

The development and validation of a LP follows a process that begins with the development of the construct map. In a previous study (Costa et al., 2023), this conceptual structure was drawn up with the students' hypothetical levels of explanation for the propagation of sound in air. However, it is necessary to check that the levels described conceptually in this structure, the construct map, are elucidated with the application of the data collection instrument (pre-/post-test). In other words, whether the descriptions correspond to the possible explanations given by another group of students. To validate this, the construct map is the starting point for this study.

It is also necessary to check whether there is a hierarchy between the levels described in the construct map, whether their descriptions are cumulative regarding scientific knowledge, and whether the hierarchy is maintained at the different times the tests are applied. It also seeks to understand the evidence of progression in students' explanations given in tests taken before and after an intervention centered on LPs.

The study was conducted through the administration of a pre- and a post-test, with the intervention of a teacher on the topic of sound, specifically targeting the research hypotheses and presenting evidence of the quality of the developed LPs.

Instrument & Procedure

This investigation took place in two 11th grade classes of a public secondary school. The sample was randomly selected from the group of students taking part in a national project. A total of 37 students participated in the study, with 21 male and 16 female students. They completed both a pre- and a post-test consisting of the same questions about sound propagation in air. The test was designed to include a real-life scenario, presenting an illustration of a man speaking and a woman listening (**Appendix A**), followed by four open-ended questions about this situation.

The pre-test was conducted at the beginning of the school year, before the teacher taught the content of sound to the students and lasted an average of 60 minutes. The test covered aspects relating to the mechanical nature of sound, longitudinal vibration and sound as a pressure wave, the propagation of sound in different media, the role of the medium in the propagation of sound and how sound affects the medium as it propagates.

The results of the pre-test were discussed among the researchers and the teacher, who developed strategies for an intervention focused on students' LPs and based on the levels of explanation described in construct map for sound propagation in air (Costa et al., 2023). During the intervention, which lasted four weeks (12 lessons), the teacher worked with his 11th grade students on the relevant aspects for preparing a good scientific explanation, as well as the concepts relating to the content of sound needed to explain the propagation of sound in air. The teacher also discussed the alternative conceptions that were elicited in the answers to the pre-test to help the students make the transition to scientific knowledge.

The post-test was administered immediately after the intervention. The same test applied before the intervention was given again to the same students. The test lasted an average of 60 minutes, and the students were asked to respond, considering the relevant aspects for a good scientific explanation and writing down as much information as possible to explain their knowledge of the propagation of sound in the air.

The interpretation of the responses was conducted using the content analysis technique (Bardin, 1977). The

Table 2. Example of classification of progression level of responses

	Question 1 (Q1)	Student's answer	Codes assigned*	Level	Rubric
Post-test (T2)	Describe how sound propagates in air from sound source to receiver. Explain your reasoning.	*"Man will emit a longitudinal mechanical wave that will propagate through air, causing particles to vibrate & increase pressure until it reaches receiver. This process releases energy."*	P01, P07, P18, & P19	LP3	T2_Q1_LP3

Note. *According to codes & levels in **Appendix C**

Table 3. Example of transformation of progression levels into a dichotomous data system

Student	LP level	T2_Q1_LP1	T2_Q1_LP2	T2_Q1_LP3	T2_Q1_LP4B	T2_Q1_LP4A	T2_Q1_LP5B	T2_Q1_LP5A
Theo	LP3	1	1	1	0	0	0	0

students' responses were coded, corresponding to both scientific concepts and formal content studied, as presented in student textbooks and scientific books, as well as alternative conceptions and misconceptions predicted in the literature. The codes, organized into categories, are available in **Table B1** with the rubric codes (**Appendix B**), and this process is detailed below. The non-normative elements in **Table B1** correspond to the alternative conceptions, misconceptions and common errors presented by the students in their explanations, as described in the literature review.

The coding was performed by four specialists secondary physics teachers: two masters in didactic of sciences and two PhD in physics. For each of the questions, one investigator (one of the authors) coded and categorized all the four responses from the 74 open-end tests (pre- and post-test). The other three experts coders coded all the responses from a sample of 20 open-end tests (27%). When there was less than 85% agreement among the expert coders, the teachers discussed the responses until reaching a higher level of agreement (Miles & Huberman, 1994). After that, the internal consistency of the coding was evaluated using Cronbach's (1951) alpha. This test was applied to the data regarding the codes assigned by the teachers to the students' responses, and it assessed the internal consistency and similarity of the coding. To assess the agreement among the coders for each code in each question, Fleiss' kappa was used (Landis & Koch, 1977).

For the assignment of LP level to each response, the construct map with its corresponding codes associated with each category in each progression level was used (**Appendix C**). The method, exemplified in **Table 1**, has been employed in previous studies (Jin et al., 2019; Plummer et al., 2015, 2020) and involves examining the codes assigned to the responses and determining the corresponding progression level from the construct map.

The assignment of levels to each response was carried out to validate the proposed hierarchy in the construct map of LPs for sound propagation in air, as well as to assess its consistency across different assessment moments. The first hypothesis of this study is that, within the hierarchical categorical structure, the higher predicted progression levels will have higher difficulty indices as they are more complex. The second hypothesis is that, if the proposed structure is valid and coherent, the hierarchical levels proposed for classifying students' explanations of sound propagation in air will remain consistent across different assessment moments (pre-/post-test).

To validate the structure, we assessed the difficulty coefficients of the categories, treated as items, based on the responses categorized in the pre- and post-test. These coefficients were generated using Rasch modelling, a unidimensional model for dichotomous data, as the categorized responses were transformed into a zero-one matrix that corresponds to the Guttman (1944) scale. The rubrics that differentiate the items (i.e., the categories) carry information about the reference test, the question, and level of progressions. **Table 2** provides a summary of categorization and assignment of a rubric. For example, results presented for the code "T1_Q4_LP1" correspond to results from "test 1" (pre-test), "question 4," "LP1 level"; results presented for code "T2_Q1_LP3" correspond to the results from "test 2" (post-test), "question 1," "LP3 level."

The explanation provided by student Theo, for example, for question 1 (Q1) in the post-test (T2) regarding sound propagation in air was classified at LP3 level, i.e., the third progression level (**Table 1**). For this question, there are seven possible levels (LP1, LP2, LP3, LP4B, LP4A, LP5B, and LP5A), as described in **Appendix C**. Since the student's response was classified at level 3, in the corresponding dichotomous response matrix for categorization, there will be three "1" values corresponding to the first, second, and third levels (as reaching the third level in the assumed Guttman (1944) scale implies achieving the first two), and four "zero" values representing levels not reached (Amantes et al., 2015).

Table 3 provides an example of transforming the progression levels, represented by rubrics that correspond to categories of LPs, into a dichotomous data system for statistical modelling purposes.

For this study, among the output information provided by Rasch modelling, we analyzed the item difficulty coefficients, item fit, and characteristic curves. The infit and outfit indices, derived from mean-square statistics (MNSQ), allowed us to infer whether each level is well-fitted to the model and should remain in the hierarchical structure of categories (construct map) to be validated. These indices should fall within the range of 0.5 to 1.5. The item characteristic curves (ICCs) show the relationships between the probability of students presenting explanations at each level and the latent variable. Through ICC, it is also possible to observe the categorical and hierarchical structure of progression levels and their consistency across different test administration moments (Amantes et al., 2015; Xavier, 2018).

As mentioned above, each level, for each question, was treated as an item. Therefore, the difficulty coefficients represent their complexity, that is, how difficult each level proposed in the construct map is.

Lastly, to verify and discuss the changes in students' explanations after the instruction focused on LPs, the frequencies of progression levels were presented in slope graph. The slope graph visually represent, for this study, the changes, or differences in the frequencies of LP levels identified in the pre- and post-test.

ANALYSIS

Analysis of Written Test Responses

As discussed in the previous section, for the classification of levels, the codes (**Appendix B**) were associated with each of the responses provided by the students. For example, student Chloe explained "how sound propagates" in the given test situation with the following response:

> "Sound propagates in the air through sound waves, which are then received by nearby beings."

The codes P06, P10, and P15 were assigned to this response (according to **Appendix B**). There is conceptual correspondence with LP1 level ("sound propagates from the source to the receiver in all directions through sound waves") when compare the assigned codes with the construct map (**Appendix C**). Thus, the student's response was classified at that progression level.

Similarly, the response provided by student Adrian was analyzed and coded, and it is, as follows:

> "The sound source starts by transferring mechanical sound waves, where in these waves there are particles that vibrate according to the zones of rarefaction or compression. In the zones of rarefaction, there is less pressure on the particles, thus less vibration, and in the zones of compression, there is more pressure on the particles, thus more vibration. These vibrations can be longitudinal or transverse, that is, they are longitudinal when their direction of propagation coincides with the direction of oscillation, and they are transverse when their direction of propagation is perpendicular to the direction of oscillation. In this case, they are longitudinal vibrations. During these vibrations, only energy is transferred, not matter."

The codes assigned to the student's response were P01, P03, P05, P06, P07, P09, P10, P11, and P18 (**Appendix B**). Upon comparison with the construct map (**Appendix C**), it is observed that responses containing all these codes, for question 01, are classified at LP5A level, as they exhibit all the expected evidence for the higher level of explanation anticipated.

The categories, codes and data were processed using the Atlas.ti software (version 23.2.1.26990). The same process was carried out to analyze and categorize all the responses to the four questions from all the students, both in the pre- and post-test.

For inter-judge reliability, the data were analyzed using IBM SPSS Statistics software (IBM Corp., 2020). The results showed Cronbach's alphas of 0.81 for the pre-test and 0.89 for the post-test, indicating internal consistency and similarity in code assignment. Regarding the agreement between the coding of the investigators in both tests, the lowest Fleiss' kappa value was 0.30, and the highest was 1.00 (p-value<0.05). This suggests a good agreement between the investigators' coding and that the agreement between the assignments is significantly different from what would be expected by chance. For the pre-test, the average kappa was 0.77 (standard deviation [SD]=0.23), with a median of 0.82. For the post-test, the average kappa was 0.89 (SD=0.15), with a median of 1.00. These results indicate almost perfect agreement in coding among the evaluators (Landis & Koch, 1977; Matos, 2014), allowing us to infer that there is reliability between the assigned codes and the responses.

FINDINGS

Learning Progressions for Sound Propagation in Air

A matrix was constructed with the responses of all 37 students for the four questions administered in both the pre- and post-test, in a dichotomous data structure for Rasch modelling, as outlined in **Table 2**. The matrix was inputted as the data source for the R software (R Core Team, 2013), and the analysis was conducted using the Rasch dichotomous unidimensional model. The Cronbach's alpha for the matrix data was 0.873, indicating good internal consistency of the scale and correlation between the levels for these tests.

Before initiating the analysis, several assumptions for Rasch modelling were considered. All levels of LP that were not attained by any of the students, as well as the levels that were attained by all students, were excluded. For the pre-test, in questions 1, 2, and 3, the highest level observed was LP3, and for question 4, it was LP4.

Table 4. Difficulty coefficients of LP levels

Question	LP level	Pre-test	Post-test
Question 01	LP1	-3.000	
	LP2	2.066	-3.000
	LP3	2.392	-2.001
	LP4B		-0.709
	LP4A		-0.285
	LP5B		0.766
	LP5A		0.940
Question 02	LP1	-2.208	-3.000
	LP2	2.392	-0.567
	LP3	3.312	-0.002
	LP4B		1.325
	LP4A		2.066
	LP5		4.121
Question 03	LP1		-2.697
	LP2	1.125	-1.303
	LP3	2.066	-0.144
	LP4B		0.143
	LP4A		0.601
	LP5		4.121
Question 04	LP1	-1.632	-4.643
	LP2	-0.853	-2.697
	LP3	-0.144	-1.632
	LP4	3.312	-0.999
	LP5		0.766

Additionally, for question 3, explanations were only provided at LP2 and LP3 levels, with LP1 level excluded from this question. For the post-test, all students provided explanations at levels higher than LP1 for question 1, resulting in the exclusion of LP1 from the analysis of difficulty coefficients.

Table 4 presents the difficulty coefficients of the levels for the pre- and post-test, for the four questions administered in the tests, on the logarithmic interval scale, the logit. Logit represents a logarithmic unit of measurement that allow for the comparison of individuals' abilities and item difficulties on the same scale, providing a quantitative interpretation of the results (Amantes et al., 2015; Xavier, 2018). For example, an item with a difficulty of 0 logit is considered to have average difficulty, while an item with a difficulty of 1 logit is considered more difficult than the average item.

As expected, for the pre-test, higher levels were not elucidated in the students' responses since they had not received instruction from LPs perspective. However, for the post-test, all levels were elucidated and, in line with the first hypothesis of this study, they showed ascending difficulty coefficients, theoretically arranged from the easiest to the most difficult level.

We observed in **Table 4** that the indices from the pre-test, considering the same item, are higher than those from the post-test. Analyzing the difficulty coefficients of LP levels for question 01, for example for the pre-test, the explanations with the upper level of complexity were classified, at most, at LP3 level. This level revealed a difficulty coefficient of 2.392 logits. However, in the post-test, LP3 level presented a difficulty coefficient of -2.001. It is also important to note that the post-test found explanations classified at the highest level of progression (LP5), which had a difficulty coefficient of 0.940 logits (lower than LP3 in the post-test). A decrease in the difficulty coefficient indicates that the item became "easier" from one test to another, serving as the first indication of learning due to instruction in the perspective of LPs. The fact that the more complex items only appear in the post-test, still with a high difficulty coefficient, also indicates progression in the learning of the presented explanations.

Another result that can be observed from **Table 4** is the maintenance of the hierarchy of difficulty coefficients of the items between the pre- and post-test. In both tests, it is observed that the levels considered theoretically less complex when constructing the categorical system of LPs had a lower empirical difficulty in being elucidated than those theoretically established as more complex. This result relates to two important aspects of validation:

(1) the constructed categorical system proves to be suitable for classifying the responses to the formulated questions, and

(2) the theoretical structure that establishes the levels of LPs is confirmed in terms of hierarchical complexity levels.

This means that the qualitative structure proposed in the construct maps for LPs on sound propagation in air was developed with explanations at different cumulative and hierarchically sophisticated levels. In this way, potential connections with construction maps were identified, and evidence for the validity of LPs levels for the propagation of sound in air was promoted (**Table 5**).

To further assess the issue of hierarchy, we analyzed ICCs of the questions in both tests. These curves allow us to investigate whether the levels of each question present difficulty indices in line with the theoretical assumption and whether they are maintained from one test to another. In addition to this information, ICCs also show the "distance" from one level to another, indicating whether the categories represent levels of complexity that are very close or very distant.

From ICCs of question 01 (**Figure 1**), it can be observed that there is a hierarchical structure among the levels categorically assigned in the construct map in both tests. It is also evident that this structure is maintained in both applications. For the pre-test, it confirms that LP2 (2.066 logits) and LP3 (2.392 logits) levels have difficulty coefficients that are very close to each other, while being significantly different from LP1 level (-3.000 logits). This indicates that LP1 represents a much less complex understanding than LP2, and LP2 represents a level of complexity very similar to LP3. Although the levels show good fit to LP2 (infit 0.963, outfit 1.030, p-

Table 5. Learning progressions for sound propagation in air

Level		Description
5	5A	Sound propagation in air is manifested in a longitudinal mechanical wave. Sound signal originates from a vibration, which affects nearby air particles' pressure, & they begin to vibrate around equilibrium position. In this movement, particles collide with others nearest to them & these collisions follow one another, creating compression zones (crests) & rarefaction zones (valleys) in air, which propagate in all directions, creating sound wave. Sound wave is thus a pressure wave, which transports energy without any material being transported.
	5B	Sound propagation in air is manifested in a longitudinal wave. Sound signal originates from a vibration, which affects nearby air particles' pressure, & they begin to vibrate around equilibrium position. In this movement, particles collide with others nearest to them & these collisions follow one another, creating compression zones (crests) & rarefaction zones (valleys) in air, which propagate in all directions, creating the sound wave. Sound wave is thus a pressure wave, which transports energy without any material being transported.
4	4A	Sound is a mechanical wave, which, as it propagates, affects pressure of particles of medium, which vibrate, considering direction of sound's propagation, & collide with each other creating compression zones (crests), when they are being compressed, & rarefaction (or expansion) zones (valleys), when they move away.
	4B	Sound is a wave which, as it propagates, affects pressure of particles of medium, which vibrate, considering direction of sound's propagation, & collide with each other creating compression zones (crests), when they are being compressed, & rarefaction (or expansion) zones (valleys), when they move away.
3		Sound propagation occurs from source to receptor, in a material medium in which particles of medium oscillate generating vibrations & collisions among them.
		Sound propagation occurs longitudinally from source to receptor, in a material medium in which particles of medium oscillate generating vibrations & collisions among them.
2		Propagation of sound occurs from source to receiver, in all directions, in a material medium.
		Propagation of sound occurs from source to receiver, in all directions, longitudinally.
		Sound is propagated by sound waves through vibrations & collisions among particles in medium.
1		Sound propagates from source to receiver in all directions by sound waves.
0		No evidence or off-track (only alternative conceptions and/or errors).

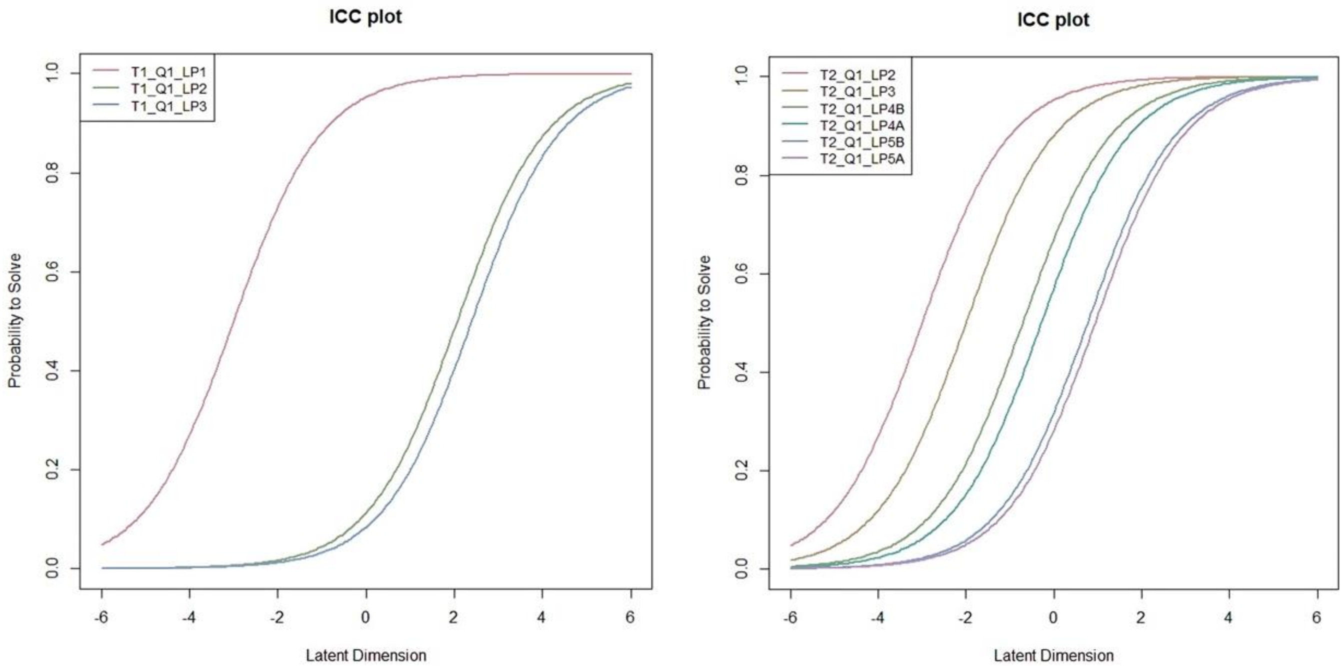

Figure 1. ICCs for question 01 (pre-/post-test) (Source: Authors' own elaboration)

value>0.05) and LP3 (infit 0.819, outfit 0.932, p-value>0.05), and the structure is maintained, it is important to consider whether such a categorical system is desirable, as it scales understanding with variable point distances. For post-test, there is greater distinction between the difficulty coefficients of LP2, LP3, and LP4B levels. But there is little difference between the difficulty coefficients of LP4B (-0.709 logits) and LP4A (-0.285 logits), as well as between LP5B (0.766 logits) and LP5A (0.940 logits). It is important to emphasize that, according to the construct map, the only distinction between these levels is that explanations classified in LP4A and LP5A levels include the information that sound is a mechanical wave, whereas explanations in LP4B and LP5B levels do not incorporate this concept. The proximity of the difficulty coefficient values between these levels reflects this slight distinction.

Table 6. Different explanations for question 01 in sublevels LP4B, LP4A, LP5B, & LP5A

Level	Explanation
LP4B	"Sound propagates through air causing vibrations in it, resulting in areas of compression (higher pressure) & rarefaction (lower pressure). It carries energy but does not transport matter, & sound is a type of longitudinal wave" (Thomas).
LP4A	"Sound is a **mechanical wave** that propagates through vibrations, also being a longitudinal wave that exerts pressure on medium, pushing particles in direction of each other, creating areas of compression & rarefaction, until reaching receiver" (Yan).
LP5B	"Propagation of sound in air, as well as in liquids or even gases, results from a longitudinal wave formed by successive compressions and rarefactions of the medium (pressure variations). The compression zones are areas where the air particles are more tightly packed, while the rarefaction zones are areas where the particles are more spread out. In terms of pressure, it varies (increasing and then decreasing), resulting in oscillation of the pressure that propagates in the air. In this example, when the man speaks, the sound particles start to vibrate, and these particles transmit this vibrational motion to neighboring particles and so on. In this way, sound propagates in all directions until it reaches the receiver, in this case, the woman" (Carolyn).
LP5A	"The sound source begins by transferring **mechanical waves**, where particles vibrate according to the zones of rarefaction or compression. In the rarefaction zones, there is less pressure on the particles, resulting in less vibration, while in the compression zones, there is more pressure on the particles, leading to more vibration. These vibrations can be longitudinal or transverse, that is, they are longitudinal when the direction of propagation coincides with the direction of oscillation, and they are transverse when the direction of propagation is perpendicular to the direction of oscillation. In this case, they are longitudinal vibrations. During these vibrations, only the transfer of energy occurs, not matter" (Adrian).

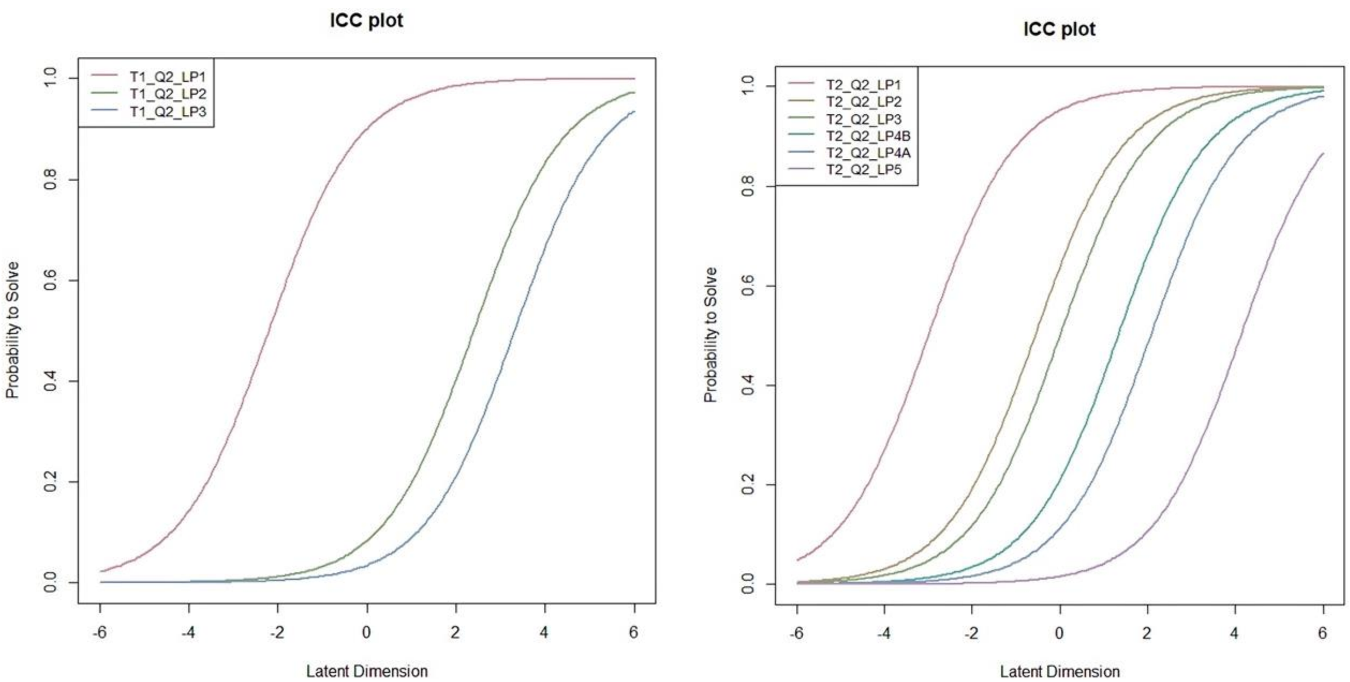

Figure 2. ICCs for question 02 (pre-/post-test) (Source: Authors' own elaboration)

The explanations provided by the students in question 01, as presented in **Table 6**, exemplify this differentiation among the aforementioned levels.

ICCs for question 02 (**Figure 2**) reveal that, in the pre-test, explanations at higher levels of complexity (LP4B, LP4A, and LP5) are not present. Additionally, there is a significant gap between the difficulty coefficients of levels LP1 (-2.208 logits) and LP2 (2.392 logits) in the pre-test, indicating that, even for the elucidation of intermediate levels, students would need to mobilize knowledge they did not yet have a strong grasp of. The hierarchical categorical structure remains preserved in both tests, and in the post-test, all levels are observed with a considerable distance between them, showing a good fit for the levels in the output data.

ICCs for question 03 (**Figure 3**) show that in the pre-test, the two elucidated levels had hierarchical difficulty coefficients with a good distance between them: LP2 (1.125 logits) and LP3 (2.066 logits).

The items also exhibit a good fit: LP2 ([infit 0.906 and outfit 0.795] p-value>0.05) and LP3 ([infit 0.903 and outfit 1.033] p-value>0.05). In the post-test, all levels were elucidated, maintaining the proposed hierarchical structure categorically in the construct maps. However,

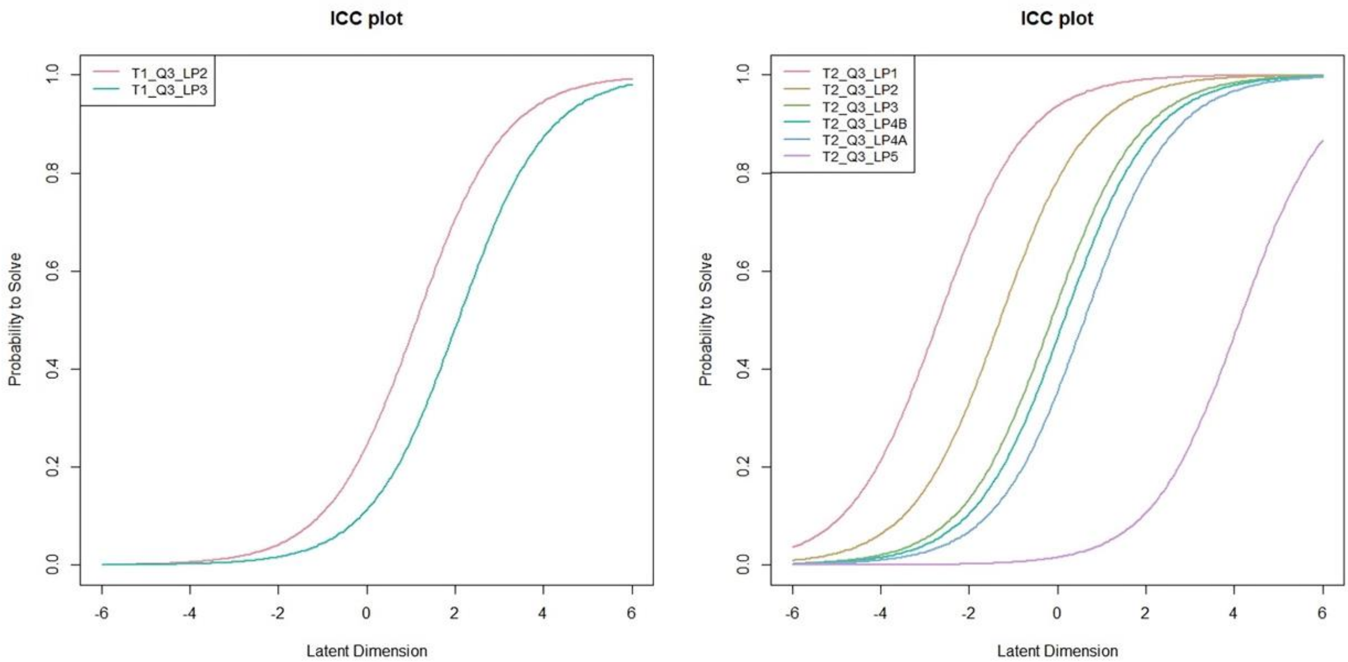

Figure 3. ICCs for question 03 (pre-/post-test) (Source: Authors' own elaboration)

there is little difference between the difficulty coefficients of levels LP3, LP4B, and LP4A.

In this question, students were expected to explain how sound affects the air as it propagates. Student Toby explained that "sound causes the air particles to vibrate as it propagates" and that "this vibration is longitudinal" (LP3). While demonstrating knowledge that particles vibrate longitudinally, there is no explicit mention, even implicitly, of the change in air pressure. On the other hand, student Elizabeth explained that

> "(...) it forms compression zones, where the air particles are more compressed and rarefaction zones, where they are more spaced apart" (LP4B).

More explicitly addressing the change in air pressure, student Beatrice wrote,

> "(…) sound affects the air as it propagates because it affects its pressure (compression zones are created, particles closer together–higher pressure–and rarefaction zones, particles more spaced apart–lower pressure)" (LP4A).

The proximity between the difficulty coefficient curves for levels LP3, LP4B, and LP4A can be justified by the fact that they present explanations with similar concepts and, thus, small differences in complexity between them. This may indicate that the conceptual difference between levels LP3, LP4B, and LP4A was not easily perceived by the students or was not adequately captured by the question items. Therefore, it should be considered for future studies whether these categories are plausible for assessing substantial differences in students' understanding of how sound affects the air as it propagates.

ICCs for question 04 (**Figure 4**) reveal, once again, that there is hierarchy within the proposed categorical structure in the construct maps, and this hierarchy is maintained in both administered tests.

In the pre-test, none of the explanations appear in the highest level (LP5), and it is observed that there is a greater distance between LP3 and LP4 curves. However, for the post-test, there is more equity in the distance between the different levels, indicating a more equidistant structure for assessing understanding.

Conceptual Changes in Students' Explanations After Instruction

To visualize the effects of instruction from the perspective of LPs, analyzing the changes in the frequencies of LPs levels in each test, we used the slope graph tool. The slope graph allows us to visually represent the changes in students' explanations after instruction by graphically representing the frequencies of the different levels assigned to each response. With this approach, we can clearly and comparatively observe how students progressed in their understanding across the levels of LPs after instruction.

Figure 5 presents the slope graph depicting the observed frequency evolution between the pre-test (test 1) and the post-test (test 2) for the elucidated levels in question 01. It can be observed that in the pre-test, the majority of students (75%) provided explanations at the lowest level of progression (LP1), while four of them provided explanations without any evidence of understanding (LP0), exhibiting errors and/or alternative conceptions about sound. However, for the post-test, there is a decrease in the frequency of lower levels, an increase in explanations at intermediate levels,

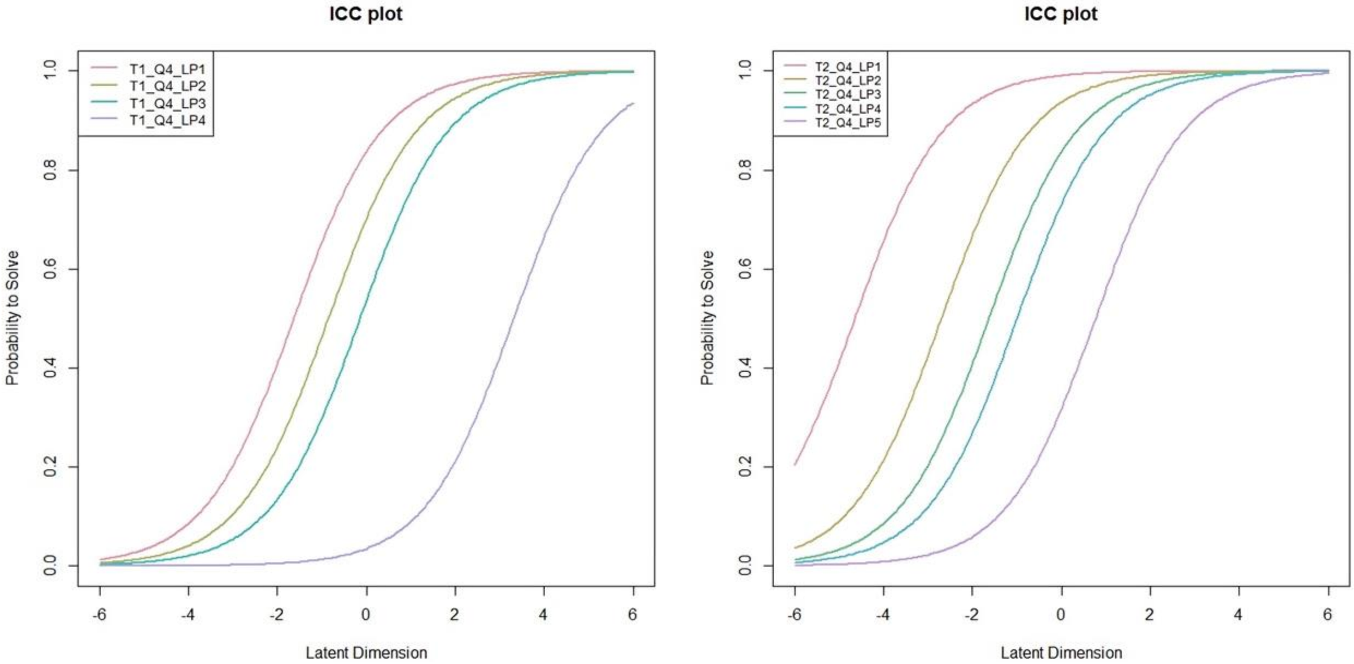

Figure 4. ICCs for question 04 (pre-/post-test) (Source: Authors' own elaboration)

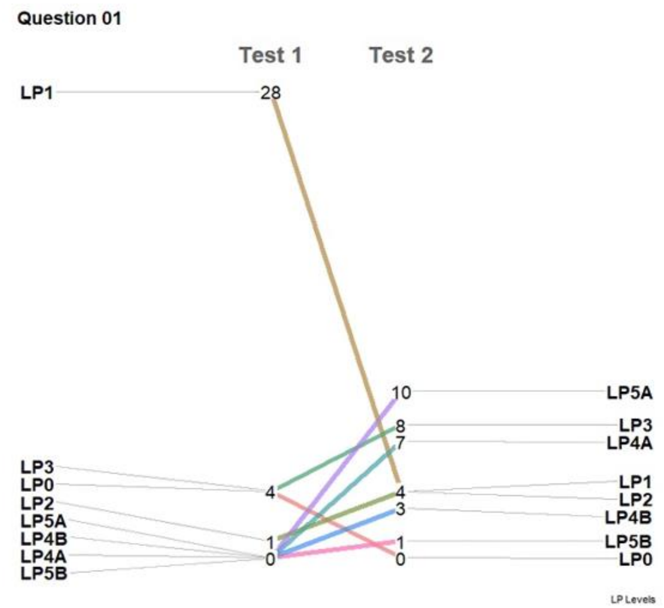

Figure 5. LP levels frequencies evolution in question 01 (Source: Authors' own elaboration)

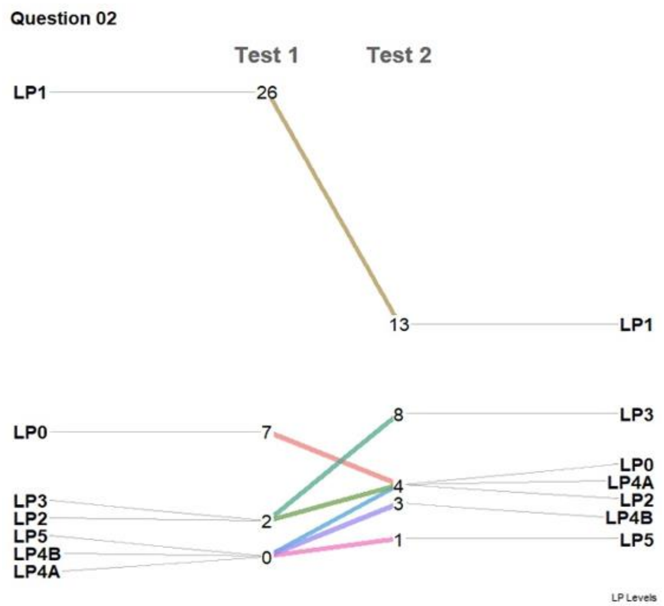

Figure 6. LP levels frequencies evolution in question 02 (Source: Authors' own elaboration)

emergence of explanations at higher level (LP5A/5B), and no explanations without evidence of learning.

For the responses given to question 02, as observed in the slope graph in **Figure 6**, it can be noted that in the post-test, there is an emergence of explanations at higher levels of complexity (LP4B, LP4A, and LP5). While in the pre-test, 70% of the students provided explanations at the lowest level of progression (LP1), this value decreased by half in the post-test. Although there are still students who provide explanations without evidence of learning, with scientific errors or alternative conceptions (LP0), the frequency of such explanations decreased in the post-test.

It is important to highlight that, although not all students were able to reach the highest level (LP5) after the instruction, there is an increase in the sophistication of their explanations when compared to the pre-test. In the pre-test, student Peter, regarding role of air, wrote:

> "Air is the medium through which sound waves propagate, in the absence of water."

The student limited their response to the fact that sound requires air to propagate, and their response was classified at LP1 level. In the post-test, although the student's response did not meet the expected level of sophistication for the highest level, as they answered:

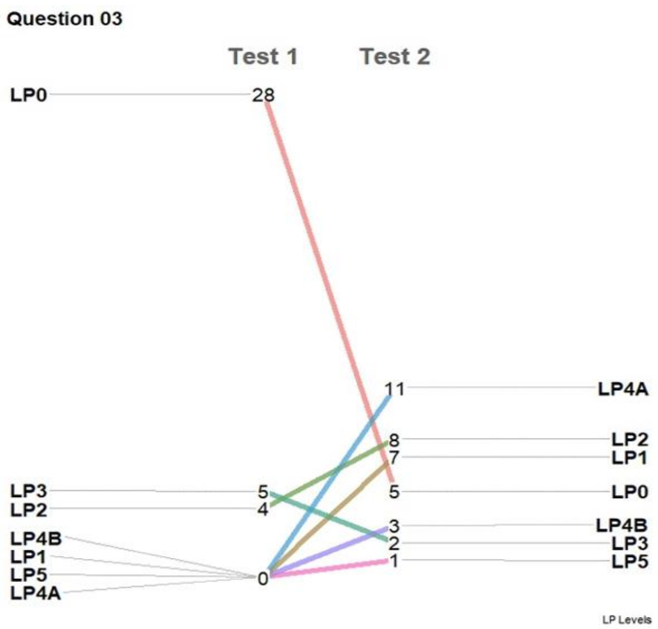

Figure 7. LP levels frequencies evolution in question 03 (Source: Authors' own elaboration)

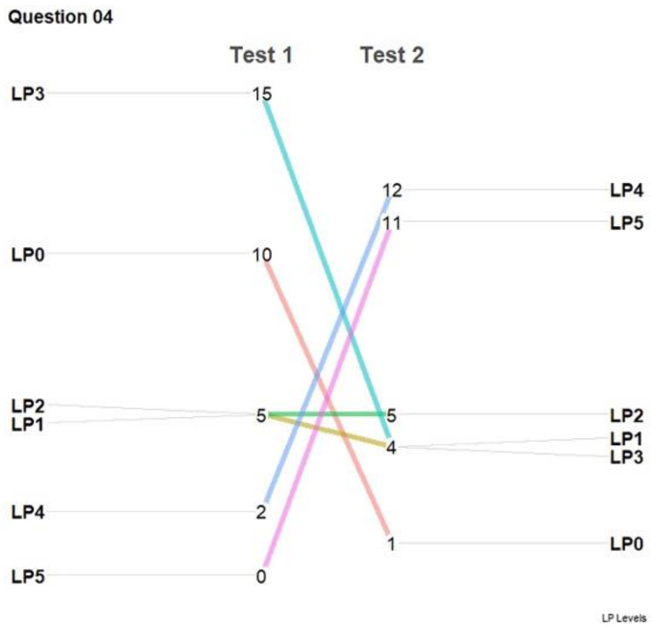

Figure 8. LP levels frequencies evolution in question 04 (Source: Authors' own elaboration)

> "Air is medium through which sound propagates, meaning that sound utilizes the particles of air to propagate (through particle vibrations)".

It was classified at LP3 level, in accordance with the assigned codes and its consistency with the construct map, as it establishes a connection between sound propagation and particle vibrations in the medium. Another example of the evolution in the degree of sophistication of explanations is seen in the case of student John. In the pre-test, their explanation ("in the process of sound propagation, air acts as the medium of propagation because it is through the vibration of air particles that sound propagates.") was classified at LP3 level. In post-test, they provided an explanation that included all expected evidence for the highest level, LP5:

> "Due to its mechanical nature, sound requires a medium to propagate. The role of air is to serve as the medium of propagation, as sound propagation in the air causes particles to vibrate."

The slope graph for question 03 (**Figure 7**) shows that in the pre-test, approximately 76% of students provided explanations without evidence of LPs, containing scientific errors and/or alternative conceptions. No student provided an explanation at LP1 level or at higher complexity levels (LP4B, LP4A, and LP5). The remaining explanations were at LP2 and LP3 levels. It is possible that the question did not provide enough cues for students to address specific concepts related to the change in air pressure during sound propagation. This may have led to a tendency for students to provide explanations at LP2 and LP3 levels, which focus more on the general idea of sound propagation and particle vibration without delving into more detailed concepts. One possibility is that the content covered in this specific question, regarding how sound affects the air during propagation, is more formal and conceptually complex compared to the other questions. In the post-test, similar to the other questions, there was an increase in the frequency of explanations at higher complexity levels, and all levels were elucidated.

The question 04 aimed to assess whether students knew that sound does not propagate in a vacuum and their possible explanations. Despite this being a concept discussed in previous school years, in the pre-test, 27% of students provided explanations without evidence of progression, containing errors and/or alternative conceptions (LP0), as shown in **Figure 8**. However, through **Figure 8**, it can be observed that between the pre- and post-test, there is an increase in the frequency (about 62%) of explanations at higher complexity levels (LP5 and LP4).

An interesting example of explanations that demonstrate elements indicating progression after instruction is that of student Anne. In the pre-test, although she knew that sound does not propagate in a vacuum, she still held alternative conceptions when she explained that

> "sound propagates through the empty spaces of the air and since there is no air (i.e., if we are talking about a vacuum), its propagation in a vacuum will not be possible" (LP1).

In the post-test, she provided an explanation with all the expected elements for the higher level of progression in this question:

> "Sound is a mechanical wave and requires a physical medium to propagate. Therefore, the density of the air will directly affect its propagation. The more particles (dense) the medium has, the better the propagation; the fewer particles the medium has, the worse the propagation. Considering that a vacuum is the absence of air, it is expected that sound does not propagate there" (LP5).

DISCUSSION

Like other studies, this investigation employed an evidence-based approach (Jin et al., 2019) to develop LPs on the propagation of sound in the air. The hierarchical levels of conceptual complexity were validated, their maintenance at different moments of application was assessed, and students' progress over a period was evaluated.

Jin et al. (2019) proposes a validation framework for investigations in LPs in science. The framework is based on an iterative approach and includes analysis of the progression's structure, empirical validation, external validation, and continuous review. The study also provides examples of applying the framework to three different LPs in science, offering insights into how these progressions can be validated and improved. The key findings highlight the importance of a systematic and comprehensive approach to validating LPs in science, as has been done in the current study.

In this study, to verify the research hypotheses, the Rasch model, chosen for validating the hierarchical levels, proved to be a suitable statistical analysis approach in the context of LPs. It can be applied even with relatively small samples (from 30 students onwards) (Commons & Miller, 2015; Xavier, 2018). Despite the study being conducted with a relatively small sample size (n=37) and four assessment items, the model exhibited good fit of MNSQ for all items and good reliability, indicating the validity of the proposed structure to interpret students' LPs.

ICCs graphically demonstrated the distance between the elucidated levels in each of the tests. In the pre-test, there is a greater distance between the few elucidated levels in each question, whereas in the post-test, all levels are present and show a greater distinction between the difficulty coefficients. A comparative analysis between the difficulty coefficients of the items in the pre- and post-test shows that the instruction provided from the perspective of LPs allowed students to provide explanations with greater sophistication. In the pre-test, for question 01, LP1 level had a difficulty coefficient of -3.00 logits, and explanations with higher levels of sophistication were found in LP3 level, with a difficulty coefficient of 2.392 logits. In the post-test, there were no explanations in the lowest level (LP1) anymore, and the difficulty coefficient for the highest level (LP5A) became 0.940 logits. Through **Table 3**, it can be observed that the same trend occurred for all questions in the test, indicating that the items became easier from one moment to another.

For question 02, in pre-test, the difficulty coefficient for LP1 level was -2.208 logits, while the highest elucidated level, LP3, had a difficulty coefficient of 3.312 logits. Although in post-test the difficulty coefficient for LP1 level decreased to -3.000 logits, difficulty coefficient for the upper level, LP5, of this question was 4.121 logits. This difference in difficulty shows that students faced challenges in understanding the more advanced concepts related to the role of air in sound propagation (Giolino & Gomes, 2015; Wright & Stone, 2004).

It was observed that the difficulty coefficients in question 03 were close between LP2 level (1.125 logits) and LP3 level (2.066 logits) in the pre-test. These values indicate that students faced difficulties in understanding the nuances and more advanced concepts of how sound affects the air as it propagates (Giolino & Gomes, 2015; Wright & Stone, 2004). In the post-test, there was a notable transformation in the difficulty coefficients. LP1 level (-2.697 logits) had the lowest difficulty coefficient, indicating that students were able to grasp fundamental concepts about how sound affects the air. Additionally, LP2 (-1.303 logits), LP3 (-0.144 logits), LP4B (0.143 logits), LP4A (0.601 logits), and LP5 (4.121 logits) levels were also elucidated, demonstrating a progressive advancement in students' understanding. The negative values of LP1, LP2, and LP3 levels in the post-test indicate that students were able to comprehend fundamental concepts in a more comprehensive way. Furthermore, the presence of LP4B, LP4A, and LP5 levels in the post-test shows that some students were able to achieve a more advanced understanding, incorporating concepts such as zones of compression, rarefaction, and changes in air pressure.

Finally, for question 04, in the pre-test, the difficulty coefficients indicated a considerable difference between LP1 level (-1.632 logits) and LP2 level (-0.853 logits). This suggests that students had difficulties in understanding the differences between the propagation of sound in an air-filled space and in a vacuum. LP3 level (-0.144 logits) indicated an intermediate understanding, while reaching LP4 level (3.312 logits) was considered more challenging for students. In the post-test, a significant change in the difficulty coefficients was observed. LP1 level (-4.643 logits) had the lowest difficulty coefficient, suggesting that students were able to understand more clearly the differences in sound propagation in air-filled and vacuum spaces. LP2 (-2.697 logits), LP3 (-1.632 logits), LP4 (-0.999 logits), and LP5 (0.766 logits) levels were also elucidated, showing a progressive advancement in students' understanding and indicating that it was easier for students to provide explanations at the upper level.

The analysis of explanations provided by students in the written tests allowed us to observe that in the pre-test, there were no explanations in higher levels of progression. This can be interpreted as an inference that, at that time, students had not yet received instruction from the perspective of LPs, and therefore did not provide explanations with the elements that guarantee a more complex understanding of the subject matter and the required scientific rigor. The randomness of responses in the initial stage, due to students not having received specific adequate instruction on the content, results in diffuse responses with common misconceptions and errors. This can lead to large distances between difficulty coefficients, as well as overlaps of categories and response classifications. Thus, analyzing levels after instruction provides better differentiation between responses, more concise inferences, improved results, and better-fitting items (Semak & Dietz, 2014; Semak et al., 2009).

CONCLUSIONS

In a LPs approach in science education, as a tool to perceive how students explain a certain science topic and how their reasoning progresses (Smith et al., 2006), it is necessary to examine the previous stages in which the content was taught, the level of depth required, and whether there are still alternative conceptions and misconceptions about the topic.

The validation of LPs ensures that they are based on solid and conceptually grounded evidence. This means that they represent the conceptual development of students in a specific domain of learning. Moreover, validation allows for assessing the effectiveness of progressions as teaching and assessment tools. By verifying their utility and efficacy, educators can make informed decisions on how to implement and adapt progressions to enhance student learning.

Our results demonstrate that the proposed LPs present explanations organized in hierarchical levels regarding the propagation of sound in air. The higher levels have higher difficulty coefficients, while the lower levels have lower difficulty coefficients. It is also evident that the proposed structure is valid and consistent, as the hierarchies of the levels proposed for the classification of explanations are maintained across different application moments (pre-/post-test)

These results reinforce the importance of instruction in perspective of LPs to promote a more comprehensive development of students' understanding of sound propagation. The proposed categorical hierarchical structure in the construct maps proved to be effective in capturing the conceptual differences between levels of understanding, allowing for a more accurate assessment of students' conceptual progress.

The slope graph provided a valuable perspective on how the frequency of progression levels changes across different test application moments (Plummer et al., 2020). It was observed that in the post-test, there was a decrease in the frequency of explanations with lower sophistication (lower and intermediate levels) and an increase in explanations with higher scientific rigor (upper level).

This may indicate that the randomness of responses in the initial stage, mainly due to a lack of more complex knowledge, provided less precise visibility of the categorical system. The fact that the structure improved in the second stage is an indication of the validity of the structure and of students' learning, as the improvement in model fit indices can be interpreted in the literature as an evolution of understanding (Semak & Dietz, 2014; Semak et al., 2009).

A construct map consolidates into a LP when it is used to assess a particular concept and/or topic based on research evidence about how students learn; when it provides examples of how students can demonstrate their knowledge and understanding at different levels of development; when it is used to plan teaching strategies and assess student performance (Plummer et al., 2015, Rogat et al., 2011). The methodological processes adopted, as well as the results presented, provided evidence that ensures the required premises in LPs approach. This evidence supported the development and validation of LP on propagation of sound in the air.

LPs approach provides valuable guidance for teachers' practices, as they can establish the best strategies to improve students' scientific knowledge based on what their students already know. LPs are also a good way to organize teaching and learning and the science curriculum, as it encourages reflection and dialogue among researchers, teachers, and assessors (NRC, 2007).

Limitations & Future Perspectives

For future studies, it is important to consider these results and reflect on the formulation of additional questions to achieve a more comprehensive assessment of students' understanding of sound propagation in other media.

Although the levels demonstrate a good fit and the hierarchical structure is maintained, there is always room for improvement in the evaluation items to provide more detailed information about students' responses. This can ensure that the differences in difficulty coefficients better reflect substantial differences in understanding between the levels.

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Ethical statement: The authors stated that both questionnaires were done anonymously. All names presented in this study are pseudonyms to ensure anonymity of participants. According to Ethical Committee at Universidade de Lisboa, informed consent was obtained from all subjects involved in this study (approval number: 4365).

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Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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APPENDIX A: WRITING TEST

Let´s Talk About Sound Propagation?

Sound propagation in air

1. Consider the situation illustrated in **Figure A1** that represents a man speaking (the sound source) and a woman listening to the man's voice (the sound receiver). Describe how sound propagates in the air from the sound source to the receiver. Explain your reasoning.

Figure A1. Open-ended question on the propagation of sound in the air (adapted from Hrepic et al., 2010 and the comic that have been developed using Pixton.com)

2. What is the role of air in the process of sound propagation?
3. Does sound affect the air as it propagates? If so, how?
4. Does sound propagate in the same way in a space with air and in a space without air (vacuum)? Explain your answer.

APPENDIX B: RUBRIC CODES FOR SOUND PROPAGATIONS IN THE AIR

The rubric codes and categories in **Table B1** were used to code the questionnaire responses and for the development of a construct map for sound propagation in the air.

Table B1. Rubric codes & categories (P: Sound propagation)

Category	Code	Example
No evidence/errors	P00	Student writes incorrect answers, which show no predicted code, no alternative conceptions, & no level of learning progression.
Sound classification according to its nature	P1. Sound is a mechanical wave.	Student must explain mechanical nature of sound.
	P2. Sound propagates in a material medium.	Student's response presents evidence that student knows that sound only propagates in material media.
	P3. Sound is a pressure wave.	Student's answer provides evidence that student knows that propagation of sound gives rise to pressure variations in space.
	P4. Sound is matter.	**Non-normative**–Students believe that sound is made up of "sound particles".
Sound classification according to its vibration	P5. Sound is a longitudinal wave.	Student must explain that sound is a longitudinal wave.
	P31. Sound is a transversal wave.	**Non-normative**
Sound propagation in air	P6. Sound propagates from source to receptor.	Student identifies source and/or receptor.
	P7. Sound transfers energy to the medium in which it propagates.	Student's explanation presents evidence that sound transfers energy to the medium in its propagation.
	P8. Sound propagates through collisions among particles in medium.	Student explains that sound propagates through collisions among particles in the medium.
	P9. Sound creates compression & rarefaction zones in medium.	Student should explain that during the propagation of sound, there are zones where the air becomes less dense (rarefaction zones) and zones where the air becomes denser (compression zones).
	P10. Sound propagates by waves.	Student refers to sound propagation limiting it to propagation by sound waves.
	P11. Sound propagates through particles in medium.	Student explains that sound propagates through the particles in the medium but does not refer to the collisions that occur among them.
	P12. Sound propagates through vocal cords.	**Non-normative**–Student explains that sound is propagated or generated by vocal cords.
	P21. Sound spreads in air.	**Non-normative**–Student writes that propagation of sound occurs because sound spreads in air.
	P22. Sound propagates in all directions.	
	P23. Sound propagates because there is no barrier preventing it from passing.	**Non-normative**
	P24. Sound propagates by reflection.	**Non-normative**
	P25. Sound propagates through empty spaces between particles of medium.	**Non-normative–**"Infiltration"
Sound in vacuum	P13. Sound cannot propagate in vacuum.	
	P14. Sound propagates in vacuum.	**Non-normative**
Role of air in sound propagation process	P15. Air is a propagation medium for sound.	Student identifies air as medium of propagation in his/her explanation.
	P16. Air makes sound propagate faster or slower.	**Non-normative**–Student relates medium's role to speed at which sound propagates rather than condition for it to propagate.
	P29. Air enables sound to propagate	**Non-normative**–Student uses verb allow to justify role of air in propagation of sound but does not refer to medium as condition for propagation of sound.
	P30. Air carries sound.	**Non-normative**
How does sound affect air as it propagates?	P17. Air vibrates in same direction as sound.	Student does not write that sound is a longitudinal wave, but his explanation provides evidence that he knows that air vibrates in same direction that sound vibrates.
	P18. Sound affects air pressure.	Student's answer, even if it does not present expected scientific concepts (it does not make explicit, for example zones of compression & rarefaction & that sound is a pressure wave), presents evidence that he knows that sound affects air pressure as it propagates.
	P19. Sound as it propagates, moves particle of air.	Student explains that sound while propagating, moves (and/or) causes vibrations/perturbations in particles in medium, but does not make explicit collisions between them.
	P20. Sound, as it propagates, does not affect air.	**Non-normative**
	P26. More dense media hinder propagation of sound.	**Non-normative**
	P27. Air affects sound in its propagation.	**Non-normative–**Students do not realize that it is sound that affects environment.
	P28. Air facilitates and/or hinders propagation of sound.	**Non-normative–**In this case, student does not relate medium as a condition for propagation of sound but as what facilitates or hinders its propagation.

APPENDIX C: CONSTRUCT MAP FOR SOUND PROPAGATION IN THE AIR

Table C1. Codes defined for each categorization of LP levels in construct map for sound propagation in air

Level		Description	Sound nature & vibration	Sound propagation in air	Role of air in sound propagation	How does sound affect air as it propagates?	Sound in vacuum
5	5A	Sound propagation in the air is manifested in a longitudinal mechanical wave. The sound signal originates from a vibration which affects the nearby air particles' pressure, and they begin to vibrate around the equilibrium position. In this movement, the particles collide with others nearest to them and these collisions follow one another, creating compression zones (crests) and rarefaction zones (valleys) in the air which propagate in all directions, creating the sound wave. The sound wave is therefore a pressure wave which transports energy without any material being transported.	P1, P2*, P3 &/or P18, P5 &/or P17	P6*, P10* P7, P8 or P19, & P9	P1*, P2, P10*, P19, P15*, & P7	P5, P7, P9*, P17*, P18 &/or P19	P1*, P2, P5*, & P13,
	5B	Sound propagation in the air is manifested in a longitudinal wave. The sound signal originates from a vibration which affects the nearby air particles' pressure, and they begin to vibrate around the equilibrium position. In this movement, the particles collide with others nearest to them and these collisions follow one another, creating compression zones (crests) and rarefaction zones (valleys) in the air which propagate in all directions, creating the sound wave. The sound wave is therefore a pressure wave which transports energy without any material being transported.	P2, P3 &/or P18, P5 &/or P17	P6*, P10* P7, P8 or P19, & P9			
4	4A	Sound is a mechanical wave which, as it propagates, affects the pressure of the particles of the medium which vibrate, considering the direction of the sound's propagation, and collide with each other creating compression zones (crests), when they are being compressed, and rarefaction (or expansion) zones (valleys), when they move away	P1, P2*, P5 or P17, P7* P3 &/or P9 &/or P18	P6*, P10*, P8 or P19, & P9	P1 and/or P2, P15*	P9, P17 &/or P18 &/or P19	P2, P13, P11*, P18*, & P19*
	4B	Sound is a wave which, as it propagates, affects the pressure of the particles of the medium which vibrate, considering the direction of the sound's propagation, and collide with each other creating compression zones (crests), when they are being compressed, and rarefaction (or expansion) zones (valleys), when they move away.	P5 or P17, P7*, P3 &/or P9 &/or P18	P6*, P10*, P8 or P19, & P9	P10*, P2, P15*, P29*	P9	
3		Sound propagation occurs from the source to the receptor, in a material medium, in which the particles of the medium oscillate generating vibrations and collisions among them.	P2 (or P1), P18* (or P9*), & P7*	P6*, P10*, P11* P8 or P19	P10*, P15*, P8 and/or P19	P19 and/or P8 & P7	P2, P13, & P30
		Sound propagation occurs longitudinally from the source to the receptor, in a material medium, in which the particles of the medium oscillate generating vibrations and collisions among them.	P5 &/or P17 P18* (or P9*), & P7*	P6*, P10*, P11* P8 or P19	P7 or P11	P5, P19 &/or P7 &/or P8	
2		The propagation of sound occurs from source to receiver, in all directions, in a material medium.	P2 (or P1)	P6*, P10*, P11* P12* and/or P22	P10*, P15*, P2	P19 &/or P28	P13, P11*, & P15*
		The propagation of sound occurs from source to receiver, in all directions, longitudinally.	P5 (or P17)	P6*, P10*, P11* P12* and/or P22	P10*, P15*, P17 and/or P18 and/or P22, P30*	P3 or P18 or P9	
		Sound is propagated by sound waves through vibrations and collisions among particles in the medium.	P7* (or P19*)	P10*, P8 or P19	P10*, P15*, P2	P18 &/or P19	P13 & P30
1		Sound propagates from source to receiver in all directions by sound waves.	P00 & P4	P6*, P12* P10 and/or P22; and/or P23, P24, & P25	P10*, P15* and/or P16 and/or P28 and/or P29 and/or P30	P28 or P26	P13 (&/or P24 &/or P25 &/or P26 &/or P28)
0		No evidence or off-track (only alternative conceptions and/or errors).	P00 & P4	P00, P12, P21, P23, P24, P25, & P26	P00, P16, P29, & P30	P00, P4, P20, P26, P27, & P28	P00, P14, P23, P24, P26, & P28

* Codes that may appear in level but are not required for progression checks.