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Construct map development for the propagation of sound in the air

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Abstract

Learning progressions describe how students can explain a concept at successive levels of increasing sophistication based on coherent ideas, instruction, and prior experiences. Most of the research on learning progressions begins with the development of the construct map, and this study will explore the processes for its development. The study presents how different levels of sophistication of students' explanations for the propagation of sound in the air can be described. 126 students from 7th to 12th grade participated in this study, which focused on describing students' explanations for the propagation of sound in the air at different levels of sophistication. An open-ended question test and a semi-structured interview seeking to capture evidence of the different levels of explanation for the propagation of sound in the air were conducted. The consistency between the preliminary construct map with evidence from tests and interviews was checked. The data displayed consonance between the construct map and the explanations provided by the students. Through the concrete evidence of how students explain this phenomenon, it has been possible to describe the levels of the construct map. This has enabled the presentation of a tool to support teachers in developing strategies and practices in learning progressions approach. For future studies in learning progressions, seek to find evidence of the paths taken by students to attain more sophisticated explanations.

Keywords: acoustic, construct map, learning progressions, propagation of sound, science education

INTRODUCTION

In the context of students' learning assessment in science education, numerous studies have been conducted since the early 1980s seeking to understand the alternative conceptions and misconceptions mobilized by students to explain a given science topic (Alonzo & Gotwals, 2012; Krajcik, 2012; Treagust & Duit, 2008). These studies have been to identify such conceptions and ascertain how they have been elucidated in the students' explanations.

In the early 2000s, the National Research Council (NRC) in the United States of America proposed an approach centered around students' learning progressions (NRC, 2001), intending to ensure their coherence in science learning. Learning progressions are a cognitive model that focuses on understanding the ways by which students' explanations of a particular science topic become more sophisticated. That is "how the students' informal ways of thinking and reasoning develop into scientific ones" (Jin et al., 2019, p. 218) following an instruction and/or throughout their school years. Learning progressions also describe students' explanations at successive levels of increasing sophistication based on coherent ideas, instruction, and prior experiences (Duschl et al., 2011; Krajcik, 2012; Smith et al., 2006).

A significant number of studies focusing on learning progressions in science have been developed since. Some research has examined the evidence of learning progressions development (Alonzo & Steedle, 2008; Jin et al., 2019; Plummer et al., 2015), other studies have highlighted the application results in an assessment

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Contribution to the literature

- Concerning the advancement of knowledge on learning progressions about sound propagation, there remains a scarcity of comprehensive studies. This study aimed to examine the process of developing the construct map, with the hypothetical learning progression levels for the propagation of sound in the air.
- Developing the construct map through evidence collected from students' explanations is one of the premises for both validating learning progression and supporting future research.
- The study presents alternative conceptions and common errors regarding the sound content. Identifying these conceptions and errors can help the teacher to establish teaching strategies that support students in the transposition to scientific knowledge.

approach (Jin et al., 2013; Plummer et al., 2020; Steedle & Shavelson, 2009) and others research have presented, in a single study, students' elaboration process and its application (Hernández et al., 2015; Jin et al., 2019; Osborne et al., 2016) in several physics contents.

In order to develop learning progressions, students' alternative conceptions and potential changes following instruction need to be understood (Alonzo, 2011; Jin et al., 2019; Rogat et al., 2011). Furthermore, although some studies have focused on understanding students' alternative conceptions and common errors in the various topics that permeate the content of sound (Eshach et al., 2018; Fazio et al., 2008; Hernandez et al., 2012; Hrepic et al., 2010; Sozen & Bolat, 2011), the research is still scarce in this regard, particularly as far as learning progressions are concerned (Hernández et al., 2015).

To promote further knowledge on learning progressions in sound propagation in the air, taking the development of the construct map as an initial step to enhancing these strategies, this study is framed by the following research question: *How can the different levels of sophistication of students' explanations for the propagation of sound in the air be described on the construct map?*

The main goal of this study is to establish patterns to develop a construct map for learning progressions. The development of this conceptual structure provides an understanding of the hypothetical levels of sophistication of students' explanations and for future related studies on sound propagation in the air.

LEARNING PROGRESSIONS IN SCIENCE EDUCATION

According to NRC guidelines, learning progressions should describe the explanations given by students in successive and increasingly sophisticated ways of thinking, as they learn a topic of science over a period (Duschl et al., 2007; NRC, 2001). It is, therefore, crucial to highlight that they are not descriptions of the skills and/or competences that the student should have to perform the proposed task, but rather explanations that can reasonably reflect how a student has learned a particular science concept (Alonzo & Steedle, 2008; Jin & Anderson, 2012; Plummer et al., 2015).

Thus, researchers in science education consider learning progressions approach a conjectural or hypothetical model for describing the paths that students follow and how these explanations become more sophisticated after a teaching sequence or over the years in school (Alonzo & Steedle, 2008; Duschl et al., 2011; Jin et al., 2019; Rogat et al., 2011). Therefore, learning progressions approach provides strong support for practicing teachers, given the importance of the perceived level of students' expected learning at a given stage in their schooling (Alonzo, 2011, 2018; Covitt et al., 2018).

When designing a teaching sequence geared towards understanding learning progressions, it is necessary to consider what students have learned in previous years and their conceptions of the topic to be taught. While some students may present coherent explanations, but still lack the expected scientific rigor, learning progressions is a tool for both designing interventions during a teaching sequence and suggesting other approaches to be taken towards the final goal (Alonzo, 2011; Smith et al., 2006). In their assessment of learning, within the framework of learning progressions in science education, teachers go beyond the perspective of checking whether the explanation is correct or not (Alonzo, 2011; Covitt et al., 2018). This approach goes beyond the progression of the scientific idea as a disciplinary content, with the additional aim of gauging the levels of sophistication presented in the students' explanations after teaching (Krajcik, 2012).

Learning progressions, as a hypothesis for explanation development (Duschl et al., 2007), constitute a powerful tool for teachers to determine the progress of their students' learning (Alonzo, 2011, 2018; Covitt et al., 2018). They also provide additional information on the paths they have taken to explain their ideas regarding a specific phenomenon (Alonzo, 2018). This approach is a good way for an instructional organization, practice, and the assessment of science teaching learning since they foster reflection and dialogue between researchers and teachers (Alonzo, 2018; Covitt et al., 2018). Learning progressions may also indicate the goals of the instruction to the teacher, what the student is expected to learn, and whether there is consonance with the instructional practices adopted (Wilson, 2009). They also aid in the design of strategies and practices that contribute to students' ability to make suitable connections, regarding the central ideas of the topic, to transpose alternative conceptions into scientific knowledge, and to construct explanations with the degree of refinement expected at the upper level.

Some research work on learning progressions begins with construct map development, giving structure and form to assessment in order to support a learning progression approach. Construct map presents the levels of students' explanations of a topic in which the upper level is characterized by explanations that include the terms and scientific rigor expected (Wilson, 2009). This level reflects the students' expected knowledge at the end of a teaching unit. The description of this level can be supported by the core ideas found in the guiding documents for education and curriculum development, which are reflected in students' textbooks (Alonzo & Steedle, 2008; Smith et al., 2006).

The lower levels are described by less scientifically sophisticated explanations, indicative of earlier school years. Sometimes these levels are described by means of alternative conceptions or incomplete terms and information that is relevant for a good explanation. The intermediate levels consist of descriptions of explanations that gradually become more sophisticated until they reach the upper level (Wilson, 2009).

In science education, it is consensual that both alternative conceptions and misconceptions should be considered in learning progressions research (Jin et al., 2019; Plummer et al., 2015; Rogat et al., 2011). In the preliminary construct map, it is necessary to identify the alternative conceptions of the topic under assessment to support the descriptions of the lower levels of the construct maps, which, after being refined and enhanced, will give rise to the lower progression level. Although many learning progressions use alternative conceptions and misconceptions in the intermediate and lower levels, "these ideas cannot be used as learning goals, but they provide useful information for developing learning activities that target naïve ideas and use those naïve ideas as funds of knowledge" (Jin et al., 2019).

The levels laid out in the construct map represent the different explanations elucidated by students, therefore, the objectives of the assessment items should be aligned with different levels of the construct map (Alonzo & Steedle, 2008; Wilson, 2009).

Although it has been used in students' science conceptions studies, in learning progressions research, most of the research highlights that written test responses, composed only of multiple-choice items, even if well designed, may not elucidate how the student was thought, in order to explain the phenomenon. Then, open-ended items are more efficient to elucidate the students' learning progressions (Jin et al., 2013, 2019; Osborne et al., 2016; Plummer et al., 2015). Additionally, further relevant information for the research can be elucidated in the interviews. Besides providing results that support the construct map, they may also suggest the revision of written test items. They reveal a deeper insight into students' alternative conceptions and common mistakes while they elaborate their explanation (Alonzo & Steedle, 2008; Jin et al., 2013, 2019).

The development of assessment items begins with content selection, the initial writing of items, peer review (or group of researchers, content experts, teachers), interviews (recorded) conducted with students, validation of item scoring rubrics for inter-rater reliability, item administration, scoring, and finally, the ranking of responses into construct map levels (Jin et al., 2019; Osborne et al., 2016; Wilson, 2009).

METHODS

The present study examines the process of the development of the construct map for learning progressions on the propagation of sound in the air. The construct map presented in this study describes the hypothesis of how students' explanations of the propagation of sound in the air can become more sophisticated after instruction. The term hypothetical is used due to the absence of both instruction and additional empirical work. It is important to understand the paths taken by the students in their explanations after an appropriate instruction (Plummer et al., 2015; Rogat et al., 2011). The steps in the elaboration of the construct map are summarized in the diagram in **Figure 1** and discussed below.

Taking sound propagation as the main concept of this study, the aim was to investigate the following core themes surrounding this topic: the mechanical nature of sound; its longitudinal propagation; its propagation in the air; whether sound can be propagated in a vacuum; the role of air in sound propagation, and how sound affects the air in its propagation.

The upper level should describe the core idea of the topic, that is, "what the students are expected to know and be able to do by the end of the progression; is informed by analyses of the domain as well as societal expectations" (Duncan & Hmelo-Silver, 2009, p. 606-607). In the preliminary construct map, this level was elaborated through the analysis of the descriptions of students' expected performances contained in the curriculum documents that guide basic education in Portugal (DGE, 2013, 2014, 2019) and in student textbooks (Amaro & Ferreira, 2014; Bôas et al., 2016; Caldeira et al., 2017). This stage was conducted in line with the techniques of documental analysis (Bardin, 1977). The upper level was defined by evaluating the topic's central ideas. The literature review on students' alternative conceptions of the propagation of sound in the air (Eshach et al., 2018; Fazio et al., 2008; Hernandez

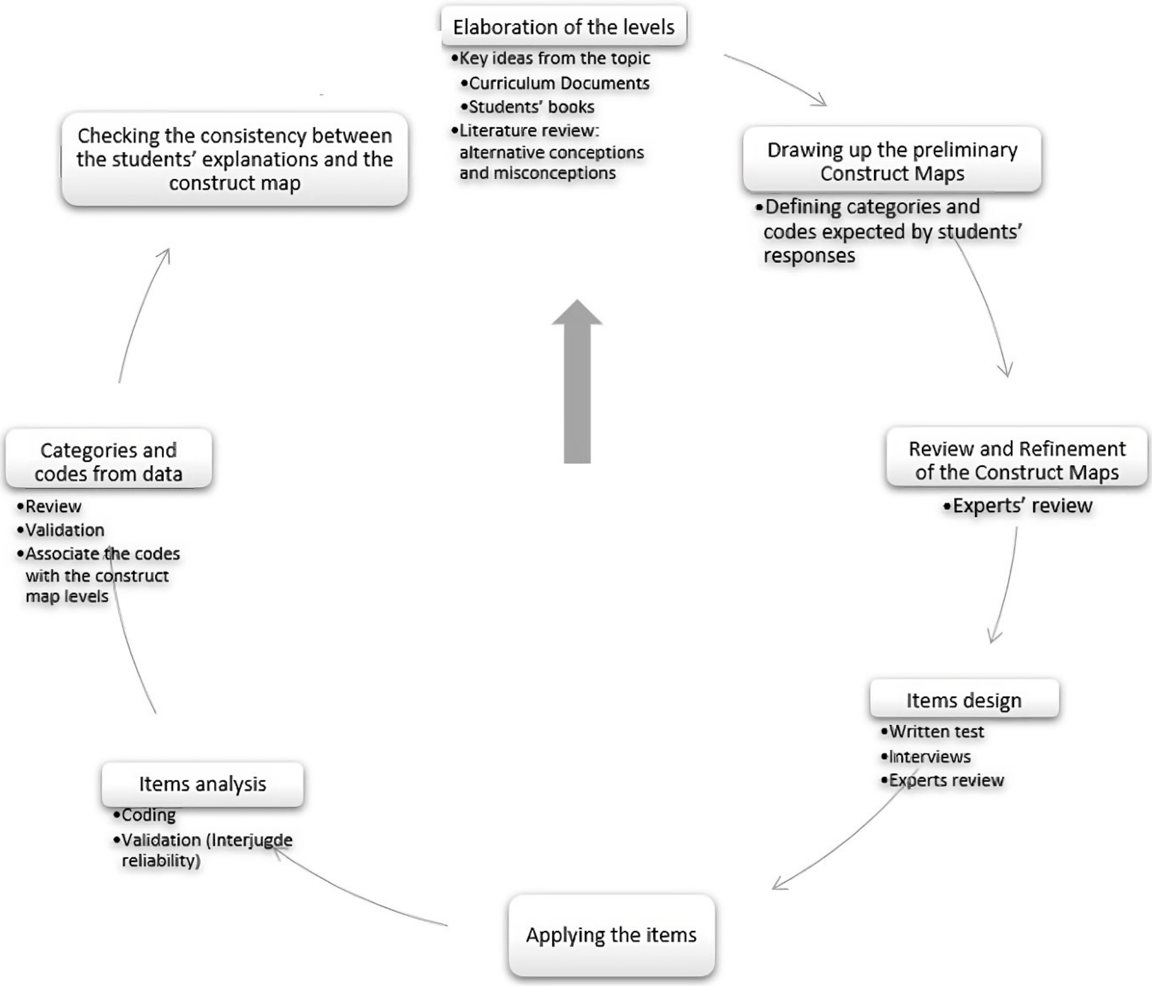

Figure 1. Process for construct map development (Source: Authors' own elaboration)

et al., 2012; Hrepic et al., 2010; Sozen & Bolat, 2011; Volfson et al., 2018) supported the elaboration of the lower and intermediate levels for the preliminary construct map (**Table 1**).

Table 1. Preliminary construct map for the propagation of sound in the air

Level	Description
4	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.
3	Sound is a mechanical wave which, as it propagates, affects pressure of 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.
2	Sound propagation occurs in a material medium, in which the particles of the medium oscillate generating vibrations and collisions among these particles. Common errors/alternative conceptions: Sound pushes the air molecules in the direction of its propagation.
1	Sound propagates from source to receptor by sound waves in a material medium through the vibration of particles in the medium. Common errors/alternative conceptions: Sound propagates only in air. Sound moves because air pushes it around. Sound passes through empty spaces among particles in medium (a property called infiltration). Sound does not affect air as it propagates. Sound propagates through vocal cords. Sound is independent–sound propagates in a vacuum (e.g., it does not need a medium). Sound propagates more easily in air than in a vacuum. Sound is a material unit of a substance or has mass. Sound is propagation of sound particles that are different from particles in medium. Sound is an entity that is carried by individual molecules as they move through medium (sound is matter). Sound exists only after it reaches listener's eardrums.
0	No evidence or off-track (only alternative conceptions and/or errors)

Take the situation illustrated in the figure that represents a man speaking (the sound source) and a woman listening to the man's voice (the sound receptor). Describe how the sound propagates in the air from the sound source to the receiver. Give an explanation of your reasoning.

Figure 2. 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)

Thus, the hypothetical levels of explanations for the preliminary construct map were reviewed and refined by the experts: five researchers in science education, four teachers with extensive experience in primary and secondary education, and 10 pre-service teachers, master's degree students in science teaching.

The literature on learning about sound has validated items, especially in terms of its propagation, and in this study, the following items were used: an open-ended item and a part of a semi-structured interview protocol, from the study of Hrepic et al. (2010), which are in line with the goal of this study. The study by Hrepic et al. (2010) focused on different themes about sound content. Both the open-ended question and the interview questions were selected according to the objectives of the preliminary construction map. It was expected that the students could explain the propagation of sound in air with all the expected evidence only with the situation described in the open-ended question.

After being revised and refined by the same experts, the assessment item (**Figure 2**) sought to ascertain how students explained sound propagation, highlighting the sound's wavelike behavior, its mechanical nature, its longitudinal propagation, how sound affects the medium in which it is propagated and the medium's role in the sound propagation process.

This study was performed with 126 students ranging from the 7th grade of basic education to the 12th grade of secondary education (53% female and 47% male, aged between 12 and 18 years), from different state schools in Portugal. The students had not received instructions on the sound contents at the time of the year level when the data were collected. They were asked to write as much as they knew about the phenomenon described, to the best of their ability. As the goal of this study is to develop a construct map, describing the different sophistication levels of explanations about the sound propagation in air, we did not do any comparisons among the groups of answers. The students responded anonymously; hence pseudonyms have been used in the data analysis.

To collect further evidence that was not elucidated in the written test answers, the same question was used in the 30 (around 25% of students) semi-structured interviews with three more questions, each lasting approximately five-10 minutes. The interviewees were selected according to two criteria: being volunteers and five students from each year level. The interviews were audio recorded and transcribed for analysis. The interview protocol presented the following guiding questions: "according to the situation presented, explain how sound propagates"; "what is the role of air in the process of sound propagation?"; "does sound affect the air while it propagates? If yes, how?"; "does sound propagate in the same way in a place with air and in a place without air (vacuum)? Explain your answer.".

The aim was to identify patterns of how students explained their ideas regarding the concepts about sound propagation with the predefined categories and rubric codes (**Appendix A**).

The categories try to elucidate the core idea of sound propagation in the air and the rubric codes referred to each category, based on the students' responses and the literature review on alternative conceptions. The so-called non-normative codes referring to misconceptions and alternative conceptions elucidated in the explanations were also included. The categories, codes, and data were processed using the "ATLAS content analysis" software.

To ensure inter-judge reliability, the data were analyzed by the first author (physics teacher and science education expert) and then by the other three authors (who are also teachers and science education experts), independently, using the content analysis technique (Bardin, 1977). It was verified a consensus among the codes attributed to the explanations of the students in the open-ended question and interviews in order to compare the analyses. A consensus of over 85% (Miles & Huberman, 1994) was observed among the categorizations performed by the authors.

The consistency between the expected rubric codes, as well as the learning progressions levels in the preliminary construct map, with elucidated codes and categories in the tests and interviews, were checked. Regarding the categories for sound propagation, they were expected to elucidate explanations related to sound classification in terms of its mechanical nature and its longitudinal vibration, how sound propagates, evidence of the need for a material medium to propagate, the role of air in the process of sound propagation and how sound affects air while it propagates.

The categories referring to the expected evidence for the explanations provided by students in the upper level were refined and the related codes were associated with them. The same procedure was adopted for the lower and intermediate levels. The students' answers were codified and classified according to each progression level in construct map presented in **Appendix B**.

RESULTS

This section presents how the levels of explanation were described in the construct map for the propagation of sound in the air based on the data in the responses to the written test, as well as in the interviews, of students from 7th to 12th grade.

The students' responses in the lower and intermediate levels (1, 2, and 3) present relatively unsophisticated explanations that frequently include alternative conceptions (Alonzo, 2011; Wilson, 2009). The responses categorized in the upper levels (4 and 5) consist of elements that ensure a more sophisticated explanation for the propagation of sound in the air with the scientific concepts expected from students in their grade (Jin et al., 2019). The respective categorizations present evidence in the construct map for the propagation of sound in the air, and some examples are presented and discussed below.

The responses provided by students who are in level 1 contain little information to explain sound propagation. These students only know that sound is a wave, as may be seen, for example, in the explanation offered by Peter (male, 11th grade): "sound propagates through sound waves emitted by the source through space in order to reach the receptor." Even though Peter also identifies that sound propagates from the source to the receptor, his explanation is devoid of the expected sophistication, hence, it was ranked at the lowest level.

Level 2 is elucidated by students who also explain sound propagation from the source to the receptor but additionally explain the presence of a material medium. For example, John (male, 10th grade) explained in the written test: "the sound produced by man propagates through the air in the shape of invisible sound waves until it gets to the woman." Although the student is familiar with the wavelike nature of sound and that it propagates in the air from the source to the receptor, he does not explain the disturbances the wave sound causes in the medium.

James's explanation (male, 11th grade) in the written test presents evidence of how sound affects the air while it propagates: "sound is a wave able to propagate through the air and other media from the vibration of its molecules. Sounds are perceived by us when they strike our ear". This explanation presents information indicating that he knows that sound propagates from the source to the receptor, in a medium, through the vibration of the molecules in the medium, hence falling within the scope of level 3. Despite indicating that sound propagates in air and other media, his explanation does not show that the student knows that sound, being a mechanical wave, only propagates in material media.

During the interaction of data analysis, student responses may lead to a division of levels into sub-levels (Alonzo & Steedle, 2008; Plummer et al., 2015). As shown in **Table 2**, level 4 has been split into sublevel 4A, which describes that "sound is a mechanical wave which, as it propagates (…)", and sublevel 4B, which describes that "Sound is a wave, which, as it propagates (…)".

In this study, some of the responses presented explanations with scientific elements, which, despite not making explicit that sound is a mechanical wave (scientific rigor of the terms to be used in explanations at upper levels), ensured their categorization at this level. This may be seen in Carolyn's (female, 11th grade) explanation of the propagation of sound in her response to the written test:

> Sound needs a material medium, solid, liquid or gaseous, to propagate (to pass from the source to the receptor), because there is no sound propagation in a vacuum. When a sound source produces a vibration, this vibration is transmitted, by shock, to the nearest corpuscles. This vibration is communicated to the next corpuscles by shocks to each other. These vibrating movements of the corpuscles (changing their positions) cause compression zones and rarefaction zones in the propagation medium.

Although Carolyn's explanation does not explicitly contain the term "mechanical wave", she considers that a material medium is needed for sound propagation and provides elements that attest to her understanding that sound affects air pressure, causing compression and rarefaction zones, propagating from the source to the receptor through the collisions of its constituents.

Finally, the responses ranked at the upper level (5B and 5A) present explanations in which all the elements expected to explain sound propagation in this situation, as well as the correct use of scientific terms, were

Table 2. Construct map for the propagation of sound in the 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 after the other, 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.
4	4A–Sound is a mechanical wave, which, as it propagates, affects pressure of particles of medium, which vibrate, considering 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. 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.
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.
2	Sound propagation is from the source to the receptor, in a material medium.
1	Sound propagates from the source to the receptor in all directions by sonorous waves.
0	No evidence or off-track (only alternative conceptions and/or errors).

evidenced. It is expected that students recognize the propagation of sound as a mechanical, longitudinal wave in the air and understand that sound is generated by a vibration that affects the pressure of nearby air particles. They are also expected to describe how collisions between adjacent air particles result in zones of compression and rarefaction, which propagate in the air in all directions and to understand that the sound wave is a pressure wave that carries energy without carrying material.

As with level 4, level 5 was also partitioned into two sublevels. As shown in **Table 2**, sublevel 5A describes that "sound propagation in air is manifested in a longitudinal mechanical wave (…)" while level 5B describes that "Sound propagation in air is manifested in a longitudinal wave (…)". Like level 4, the difference between these two sublevels refers to the mechanical nature of the sound.

This pattern was found in the semi-structured interviews in which the interviewer was able to probe the students' understanding, as may be seen in Sophie's (female, 11th grade) explanation:

> Sophie: So, sound propagates through longitudinal waves, in this case, the air is the medium of propagation, so the transmission of the wave occurs by compression and rarefaction movements, and it is through this transmission of energy, through the particles of matter, which in this case is gaseous, that sound gets to the receptor.
>
> Interviewer: And what is the role of air in the sound propagation process?
>
> Sophie: It is to transmit the wave.
>
> Interviewer: Do you think that sound affects the air as it propagates? If so, how does that happen?
>
> Sophie: Just in terms, maybe, of constituents, the atoms, and molecules of the air, because the matter will, in a certain way, transmit the sound.
>
> Interviewer: So how does the sound affect the air as it propagates?
>
> Sophie: In the area it is being transmitted it can become more compacted or distended.
>
> Interviewer: Does sound propagate in the same way in some place with air as it does in a space without air, in a vacuum?
>
> Sophie: No, in a vacuum there is no transmission of sound, since in a vacuum there are no constituents, there is no medium to propagate in, so sound does not propagate.

In Sophie's responses (level 5B), although the term "mechanical wave" does not appear, some elements indicate her knowledge that a material medium is necessary for the propagation of sound. They are also elements that reveal learning about the longitudinal propagation of sound that affects the air as it propagates, and energy transfer among the medium's constituents.

After analysis of the written tests and interviews, which led to the creation of other intermediate levels and sub-levels, the final construct map for the sound propagation in the air is reached (**Table 2**).

Furthermore, it is important to mention that some students presented explanations with errors and alternative conceptions (non-normative elements). Those who explained that "sound is propagated by ethereal particles that can be particles called sound, sound waves, or sound particles" (Hrepic et al., 2010), are particularly noteworthy, as demonstrated in Mary's (female, 10th grade) explanation: "The particles of sound, when emitted, will propagate through the air until they reach the receptor". The concept that "sound waves spread through the air and cause the sound to spread away from the source" (Fazio et al., 2008) is also worthy of note, as confirmed in Charles's (male, 8th grade) response: "the sound leaves the sound source (the man) and spreads through the air and reaches the receptor of the sound (the woman)". Some students also perceive sound as independent, that is, sound propagates through a vacuum (i.e., it does not need a medium) (Eshach et al., 2018; Fazio et al., 2008; Hrepic et al., 2010, Sozen & Bolat, 2011), such as Andrew (male, 9th grade), who wrote that "without the vacuum, I think it propagates in a normal way and you hear it well. In a vacuum you do not hear well." There were also explanations associating sound propagation to the reflection phenomenon (Hernandez et al., 2012), as in Amy's (female, 7th grade) response:

> When a person speaks the sound comes out of his/her mouth and goes towards another person. But when a person speaks, but in that place, where he or she is, the sound comes out and echoes, because it's in a closed place and the sound collides with something and goes back to the person.

Even though reverberation may also exist during this process, in environments with obstacles, the explanation shows no evidence of the progression expected according to the proposed construct map.

DISCUSSION

Research on learning progressions usually begins with the development of the construct map. It aims to find out the different levels of sophistication of students´ explanations, alternative conceptions and common errors. (Plummer et al., 2015; Wilson, 2009).

The focus of this study was primarily to describe the different levels of sophistication of students' explanations for the propagation of sound in the air. To describe these levels, the development of a construct map process was presented for the propagation of sound in the air, embodied in previous research (Plummer et al., 2015; Wilson, 2009). The data analysis presents evidence for the existence of these levels described in the construct map from students´ explanations.

Plummer et al. (2015) presented a construct map for the solar system through interviews in middle school, high school and college students. The goal is for students to understand that the observed patterns in the current solar system can be explained through a model of how it was formed. The upper level includes understanding patterns relative to the orbits of the planets, the early composition of the solar system, revealed by meteorites, and the distribution of planet compositions (with rocky, metal-rich planets close to the sun and an increasing presence of ice in the outer solar system). This description emphasizes the importance of students engaging in evidence-based explanations and making connections between different practices to develop a comprehensive understanding of the topic.

Wilson (2009) points out that construct map provides a structure that allows describing and organizing students' progress towards more advanced knowledge. The upper level refers to a complete scientific understanding of three phenomena related to the Earth and solar system domain: the day/night cycle, the phases of the moon, and the seasons in terms of the movement of objects in the solar system. This upper level was based on standards and benchmarks set out in national educational standards documents.

In the present study, the upper level was based on the central idea of sound propagation, presented in the national education syllabus and the student's textbooks. It includes that sound is a mechanical and longitudinal wave, the understanding that sound affects air pressure, and that medium particles vibrate around an equilibrium position, with the creation of compression and rarefaction zones and the transfer of energy without the transportation of matter.

The results revealed that some students referred the mechanical nature of sound but did not refer the longitudinal propagation and vice versa. The closest interview response presented the information that sound propagates longitudinally and it needs a material medium to propagate. However, this answer did not show the mechanical nature of sound.

The absence of the scientific term associated with the sound wave's mechanical nature was, therefore, the reason for proposing sublevels 4B and 5B. It was also the case with the other levels in which coherent explanations were advanced but incomplete within the scope of what is expected in the explanation of the propagation of sound.

It is also important to note that explanations with errors and/or alternative conceptions were given by students in this study. As explained in previous studies, students remain giving explanations with evidence about "sound is an entity that is carried by individuals molecules as they move through the medium (sound is matter)" (Eshach et al., 20187; Fazio et al., 2008; Hrepic et al., 2010), "sound is propagate by ethereal particles that can be particles called sound, sound waves, or sound particles" (Hrepic et al., 2010), "sound waves spread through the air and cause the sound to spread away from the source" (Fazio et al., 2008), and "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, Sozen & Bolat, 2011).

Although checking common conceptions and errors is a step in the construction map, the aim is how the different levels of sophistication of the explanations given by the students can be described. While some of the studies (Eshach et al., 2018; Fazio et al., 2008; Hrepic et al., 2010; Sozen & Bolat, 2011; Hernandez et al., 2012; Volfson et al., 2018) have been concerned with understanding what alternative conceptions students elucidated in their explanations of the sound propagation, our approach is to support teachers in their practices to help students develop explanations of how sound propagates in the air and explain the rule of the air as it propagates in different levels of sophistication.

CONCLUSIONS

Besides being part of the development of construct maps for learning progressions approach, it is important to identify the students' alternative conceptions presented during the teaching-learning process and the teacher must be the mediator that supports them in mobilizing these conceptions, reorganizing, and refining them to reach scientific knowledge.

The construct map is an important component of the learning progressions approach. It provides an organized, coherent path for students' knowledge development, enabling educators to identify learning goals and plan effective instructional strategies. The construct map allows teachers to identify gaps in the students' knowledge and plan specific instructional interventions to help them progress towards the upper level. In addition, the construct map facilitates the assessment and measurement of students' progress by providing clear criteria for evaluating performance at different stages of learning (Plummer et al., 2015; Wilson, 2009).

This study focused on the development of the construct map levels through evidence in students' explanations about sound propagation in the air. It contributes to future research and provides design instruction that supports teachers' practices. Further studies are needed to understand and characterize students' understanding of this topic and assess how their ideas expand and become more sophisticated after intervention and instruction.

As one of the instruments of the approach in learning progressions, the construct map developed in this study aimed to present different levels of descriptions of explanations for sound propagation in the air. In future research, we plan to check, with appropriate statistical treatment, whether these levels of sophistication in construct map were constructed in a hierarchical way and the instruction effects on students' learning progressions.

The next step comprises a study on learning progressions for the propagation of sound in the air, through pre/post-tests associated with an intervention with a teaching sequence on sound propagation. In the next study, it is intended to add the same interview questions to the written test. Responses to the data collection instruments revealed that as more questions were asked in the interview, more evidence of different levels of progression could be elicited. The aim here is to understand how students' explanations become more sophisticated, the levels of progression they reach, and their consistency with the levels described in the construct map.

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APPENDIX A: RUBRIC CODES FOR SOUND PROPAGATIONS IN THE AIR

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

Table A1. 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 on its vibration	P5. Sound is a longitudinal wave.	Student must explain that sound is a longitudinal wave.
Sound propagation in air	P6. Sound propagates from source to receptor.	Student identifies the source and/or receptor.
	P7. Sound transfers energy to medium in which it propagates.	Student's explanation presents evidence that sound transfers energy to 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 propagation of sound, there are zones, where air becomes less dense (rarefaction zones) & zones where 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 particles in medium but does not refer to 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
Sound in a vacuum	P13. Sound cannot propagate in a vacuum.	
	P14. Sound propagates in a 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.
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.	Although student's answer does not present expected scientific concepts, it presents evidence that he knows that sound affects air pressure as it propagates.
	P19. Sound as it propagates, moves particles of air.	Student explains that sound, while propagating, moves/vibrates/disturbs particles of the medium.
	P20. Sound, as it propagates, does not affect the air.	Non-normative

APPENDIX B: CONSTRUCT MAP FOR SOUND PROPAGATION IN THE AIR

Table B1. Codes defined for each categorization of LP levels in the construct map for sound propagation in the air

Level	Description	Sound nature & vibration	Sound propagation in air	Sound in vacuum	Role of air in sound propagation	How does sound affect air as it propagates?
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.	P1, P2, P3, and/or P18, P5, and/or P17	P6*, P10*, P7, P8, or P19, P9	P13	P15	P17 and/or P18 and/or P19
	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 sound wave. Sound wave is thus a pressure wave, which transports energy without any material being transported.	P1 or P2, P3 and/or P18, P5, and/or P17	P6*, P10* P7, P8 or P19, P9	P13	P15	P17 and/or P18 and/or P19
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.	P1, P2, P3, and/or P18	P6*, P10*, P8 or P19, P9	P13	P15	P17 and/or P18 and/or P19
	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.	P2, P3, and/or P18	P6*, P10*, P8 or P19, P9	P13	P15	P17 and/or P18 and/or P19
3	Sound propagation occurs from source to receptor, in a material medium in which particles of medium oscillate generating vibrations & collisions among them.	P2 (or P1)	P6*, P10*, P8, or P19	P13	P15	P19
2	Sound propagation is from source to receptor, in a material medium.	P2 (or P1)	P6*, P10*, and/or P22			
1	Sound propagates from source to receptor in all directions by sonorous waves.		P6*, P10, and/or P22	P13	P15	
0	No evidence or off-track (only alternative conceptions and/or errors).	P4	P12, P21, P23, P24	P14	P16	P20