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Modelling Sound in Primary Education: A Qualitative Case Study of a STEAM-Based Didactic Sequence

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Abstract

Teaching sound in Primary Education poses specific challenges because students are required to explain an everyday phenomenon whose physical functioning is not directly observable. This study examines how fifth-grade Primary Education students construct and transform their understanding of sound through a STEAM-based didactic sequence implemented in a real classroom context. A qualitative case study was conducted with two fifth-grade classes from a public school in Zaragoza, Spain, involving 41 students. Three sources of evidence were collected: students' productions, observational records kept by the first author acting as teacher-researcher, and the final product of the sequence. The corpus comprised 97 meaning units, defined as segments of student discourse representing distinct explanatory ideas. Qualitative content analysis revealed a progression from phenomenological, substantialist, or poorly articulated explanations towards formulations closer to the school scientific model of sound. Progress was especially evident in students' understanding of vibration as the origin of sound, the need for a material medium for sound propagation, and the application of the model to new situations. This study contributes to science education by showing how a STEAM-based modelling sequence can support the progressive development of scientific explanations in Primary Education. Overall, the findings suggest that integrating physical exploration, listening, sound production, and the construction of a final product can effectively support school modelling processes related to sound.

Keywords: school scientific model of sound; scientific modelling; STEAM education; music and science; scientific practices; science education

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1. Introduction

Science education in Primary Education faces the major challenge of helping students construct explanations of everyday phenomena which, despite being part of their daily experience, require conceptual models that are not directly observable. Sound constitutes a particularly relevant case within this didactic problem, since children constantly interact with sound phenomena in school, family, technological, and musical contexts. Understanding how sound is produced, how it propagates, and why it changes requires coordinating relationships between vibration, the material medium, and sound properties such as pitch, intensity, frequency, and amplitude (Butts & Smith, 1994; Eshach & Schwartz, 2006; Hrepic et al., 2010; Rico et al., 2021; Veith, 2023). These concepts are not directly observable, making them particularly challenging for students to understand. This distance between perceptual experience and physical explanation makes sound a topic of particular interest for research

in science education, especially when addressed from early ages and in ordinary school contexts (Gallegos-Cázares et al., 2021; Rico et al., 2021; Sözen & Bolat, 2011; Veith, 2023). Research with younger children has shown that sound is often interpreted through its source, receiver, or immediate perceptual effects, and that only a limited proportion of children spontaneously recognize sound propagation as a spatial process (Ravanis et al., 2021).

Previous research has consistently shown that learning about sound involves persistent difficulties across different educational levels (Eshach & Schwartz, 2006; Eshach et al., 2018; Hrepic et al., 2010; Rico et al., 2021; Veith, 2023). In particular, students often conceive sound as a substance, a material entity, or an object that moves autonomously, rather than as a phenomenon associated with vibrations propagating through a material medium. This type of interpretation has been described as a form of naive materialism, insofar as students attribute to sound properties typical of physical objects, such as moving, colliding, being stored, or being contained (Eshach & Schwartz, 2006; Eshach et al., 2018; Pozuelo, 2024). Technology-mediated inquiry environments have also been explored in elementary sound education. For example, Cai et al. (2022) implemented a two-week inquiry-based course on sound with students in grades 4–6 using augmented reality resources, highlighting the potential relevance of multisensory environments for learning science. Likewise, obstacles have been identified in understanding the need for a material medium for sound propagation, as well as difficulties in differentiating between the perception of the phenomenon and its physical explanation (Hrepic et al., 2010; Rico et al., 2021; Sözen & Bolat, 2011; Veith, 2023).

Alongside these difficulties, research has also pointed to problems in relating perceptual properties, such as pitch or intensity, to physical variables such as frequency or amplitude (Butts & Smith, 1994; J. P. Costa et al., 2024; Rico et al., 2021; Veith, 2023). In this sense, students may use everyday terms such as low-pitched, high-pitched, loud, or soft without this necessarily implying an understanding of the physical relationships that explain these perceptual differences (Butts & Smith, 1994; Rico et al., 2021; Soto & Porflitt, 2024). Therefore, everyday familiarity with sound does not guarantee its scientific understanding, nor does the incorporation of school vocabulary by itself ensure the construction of an articulated explanatory model (Eshach et al., 2018; Rico et al., 2021; Veith, 2023).

From this perspective, teaching sound cannot be reduced to the presentation of definitions or to the isolated implementation of hands-on activities. Research in science education has highlighted the importance of engaging students in school-based scientific practices (Windschitl et al., 2008). These practices include observing, comparing, formulating questions, producing evidence, justifying claims, arguing, and revising explanations on the basis of experience (Dah et al., 2024; Muñoz et al., 2020; Urdanivia Alarcon et al., 2023; Zamalloa et al., 2025). Within this model-based and inquiry-oriented perspective, inquiry and experimentation acquire value when they are not limited to the manipulation of materials, but are articulated with processes of interpretation, comparison, and conceptual reconstruction (Dah et al., 2024; Premthaisong & Srisawasdi, 2024; van Eijck et al., 2025). Problem-based and inquiry-oriented approaches have been shown to promote students' participation in scientific practices, including the formulation of research questions, hypothesis construction, experimental design, observation, data collection, information search, and communication of results (Pozuelo-Muñoz et al., 2023).

This emphasis on inquiry, experimentation, and scientific practices is especially relevant in Primary Education, where practical experiences can support scientific learning provided that they are accompanied by pedagogical mediations that help students relate what they observe to more general explanatory models (Carroll & Park, 2026; Li et al., 2025; van Eijck et al., 2025).

Scientific modelling therefore plays a central role in the teaching and learning of sound. Learning science does not only involve acquiring isolated concepts, but also constructing, testing, revising, and applying models that make it possible to explain phenomena in the natural world (Carroll & Park, 2026; Li et al., 2025; Windschitl et al., 2008). In the case of sound, modelling makes it possible to analyze how students progress from descriptions focused on what is perceptible towards explanations that coordinate vibrational origin, propagation through material media, and variation in sound properties (J. P. Costa et al., 2024; Rico et al., 2021; Veith, 2023). For this reason, it is necessary to study not only whether students reach correct answers at the end of an intervention, but also how their explanations are mobilized, sustained, transformed, or transferred throughout the teaching and learning process (Pacaci et al., 2024; Windschitl et al., 2008; Li et al., 2025).

At the same time, the STEAM approach has gained relevance as a way of integrating science, technology, engineering, arts, and mathematics into educational proposals centered on meaningful problems, experiences, or productions (Chappell et al., 2025; Filipe et al., 2024; Yim et al., 2025). Research has also shown the educational potential of hands-on STEM activities related to the physics of sound, particularly when sound phenomena are connected to meaningful social issues such as noise pollution, health, well-being, and sustainable development (M. C. Costa et al., 2023). However, several recent reviews have highlighted that not every proposal labelled as STEAM involves effective disciplinary integration. Some reviews indicate that one of the main challenges in the field is to specify how disciplines are actually articulated in the classroom and to prevent the arts from functioning merely as a motivational, decorative, or subsequently added resource (Chappell et al., 2025; Dominguez et al., 2024; Yim et al., 2025).

In the teaching of sound, the relationship between science and music is of particular interest, since both disciplines share the same object of experience, although they approach it from different perspectives (Filipe et al., 2024). While science makes it possible to construct explanations about vibration, propagation, and the physical properties of sound, music offers contexts of listening, production, comparison, variation, and sound organization that can enrich the exploration of the phenomenon (Blanco-García et al., 2025; Bravo-Fuentes et al., 2025; Eramo et al., 2025). Consequently, the integration of science and music can constitute a relevant didactic space when both dimensions are articulated around the construction of explanations about sound, and not merely used as a strategy for motivating or contextualizing scientific activity (Soto & Porflitt, 2024).

Overall, previous research consistently identifies students' difficulties in understanding sound as a vibrational phenomenon. However, considerably fewer studies have examined how these explanations evolve throughout structured classroom interventions designed to support scientific modelling. Despite the progress made in understanding students' conceptions of sound and in developing inquiry- and STEAM-based approaches, further situated studies are still needed to analyze how students' explanatory models evolve during specific didactic sequences in real Primary Education contexts. Much of the research has characterised students' alternative conceptions of sound (Eshach & Schwartz, 2006; Hrepic et al., 2010). Subsequent studies have further described the associated conceptual obstacles and mental models (Eshach et al., 2018; Rico et al., 2021; Veith, 2023). However, it is equally important to study how these explanations are transformed during classroom proposals that integrate inquiry, experimentation, modelling, and sound production (J. P. Costa et al., 2024; Carroll & Park, 2026; Li et al., 2025). This type of analysis of the evolution of students' explanatory models can contribute didactic knowledge about the conditions that favor the progressive construction of the school scientific model of sound and about the role that a pedagogically grounded STEAM integration can play (Chappell et al., 2025; Filipe et al., 2024; Yim et al., 2025).

Building on these gaps, the present study aims to analyze how fifth-grade Primary Education students construct and transform their understanding of sound throughout a STEAM-based didactic sequence implemented in a real classroom context. More specifically, the study focused on the evolution of students' explanations regarding vibration as the origin of sound, the need for a material medium for its propagation, the relationship between perceptual properties and physical variables, and the application of the model to new situations. The main results show progression from phenomenological, substantialist, or poorly articulated explanations towards formulations closer to the school scientific model of sound, especially when tasks combine physical exploration, comparison between media, sound production, and the construction of a final product. This contribution reinforces the idea that teaching sound in Primary Education can be organized as a process of school scientific modelling in which the integration of science and music acts as a context for producing, contrasting, and transferring scientific explanations.

2. Materials and Methods

2.1. Study Design

The research was framed within a broader Design-Based Research (DBR) approach, understood as a methodological framework aimed at designing, implementing, analyzing, and progressively improving educational proposals in real teaching contexts (Guisasola, 2024). Recent DBR studies in science education have used design, implementation, and evaluation cycles to analyze both students' scientific competence development and the validity of teaching-learning sequences, reinforcing the suitability of this approach for generating situated didactic knowledge (Pozuelo-Muñoz et al., 2025). This approach was considered appropriate because the general purpose of the research was not merely to apply a didactic sequence, but to generate situated didactic knowledge on how to support the construction of the school scientific model of sound in Primary Education.

While the broader research is framed within a Design-Based Research approach, this article focuses specifically on the first exploratory implementation of the proposal, which is analysed as a qualitative case study. This approach was selected to allow an in-depth analysis of how students' explanations evolved within a natural classroom setting. It also responded to the interest in gaining an in-depth understanding of how students mobilized, sustained, transformed, and applied their explanations of sound throughout the sequence, rather than experimentally measuring the generalizable effectiveness of the intervention.

The qualitative case study made it possible to analyze the phenomenon in its natural context, attend to the complexity of classroom interactions, and reconstruct the evolution of students' collective discourse from diverse sources of evidence. In this sense, the main unit of analysis was the didactic implementation as a whole, while the two participating groups functioned as internal units of observation within the same case. This strategy made it possible to identify regularities and variations between classrooms without fragmenting the analytical unity of the implemented design (Baxter & Jack, 2008; Crowe et al., 2011; Hyett et al., 2014; Kushnir, 2025; Rashid et al., 2019).

2.2. Context and Participants

The implementation was carried out in a public Primary Education school located in Zaragoza, Spain. Two fifth-grade groups participated in the study, with a total of 41 students. The choice of this educational level responded to the curricular relevance of sound content in the upper years of Primary Education and to the possibility of working on the phenomenon through exploration, inquiry, sound production, and the construction of explanations. These characteristics are relevant because they provide the educational context for interpreting the evolution of students' explanatory models throughout the didactic sequence.

The study was conducted within the regular functioning of the school and under ordinary classroom conditions. This feature was relevant because it made it possible to analyze the construction of the school scientific model of sound in an ecologically plausible context, without creating an artificial situation separated from everyday educational practice. The intervention was designed and implemented by the first author, acting as teacher-researcher, which allowed close documentation of the process, although it also required explicit attention to methodological reflexivity and to the possible impact of the dual role on data interpretation (Berger, 2015; Dwyer & Buckle, 2009).

Given the qualitative approach of the study, the sample was not selected according to criteria of statistical representativeness, but rather according to its suitability for the aim of analyzing a situated experience in depth. Therefore, the results should be interpreted as contextualized didactic knowledge and not as evidence that can be generalized in population terms. Accordingly, caution should be exercised when transferring these findings to other educational contexts with different participant characteristics or instructional conditions.

2.3. Didactic Sequence

The didactic sequence, entitled Exploring the Universe of Sound! was designed to support the progressive construction of the school scientific model of sound in Primary Education. The proposal articulated scientific practices of inquiry, experimentation, modelling, and argumentation, together with situations of listening, sound production, and sound analysis related to musical experience. This integration responded to a STEAM approach in which music did not function as a motivational add-on, but as a context for exploring, comparing, and explaining sound phenomena.

The sequence was organized into eight sessions distributed across three interrelated conceptual blocks. The first block focused on the production of sound, vibration as the origin of the phenomenon, and an initial approach to variations in pitch and intensity. The second block addressed sound propagation through different material media, including contrasting situations involving solids, air, water, and vacuum. The third block focused on the application and transfer of the model through the construction and exploration of a bottle xylophone as the final product.

This organization responded to a progressive logic. Each block revisited ideas previously addressed and introduced new situations that required students to observe, compare, justify, and revise explanations. From a didactic point of view, the sequence was not conceived as a set of independent activities, but as a school modelling pathway in which students had to construct relationships between sound production, vibration, material medium, propagation, pitch, and intensity.

The construction of the bottle xylophone acted as a task of synthesis and conceptual transfer. In order to build and explain how it worked, students had to mobilize knowledge about sound production, amount of water, vibration of air, tuning, and pitch variation. In this way, the final product made it possible to observe the extent to which the explanations constructed throughout the sequence could be applied to a new and functional situation.

2.4. Corpus and Data Collection

The corpus of the study consisted of the set of evidence generated during the implementation of the didactic sequence. It was configured as a multimodal classroom corpus comprising three main sources: students' productions, observational records kept by the first author acting as teacher-researcher, and the final product of the sequence.

First, students' productions generated during classroom activities, whole-class discussions, and shared reflection sessions were collected. These materials provided evidence of students' explanations, questions, justifications, comparisons, and reformulations related

to sound production, propagation, and modification. Second, observational records kept during the implementation of the sequence were incorporated. These records documented comprehension difficulties, moments of conceptual progress, relevant classroom interactions, and significant episodes of collective reasoning. Third, the bottle xylophone was analysed as the final product of the sequence. It was considered not only as a material outcome, but also as evidence of students' ability to apply the sound model to a new situation through conceptual transfer.

These three sources were analyzed collectively to reconstruct the evolution of students' explanations throughout the didactic sequence. Thus, the analysis focused on identifying patterns in how students' ideas developed over time, with particular attention to key conceptual shifts. Data collection was integrated into the ordinary dynamics of the classroom. It was not designed as an external extraction of data separated from educational practice, but as a progressive documentation of students' responses, productions, and actions during the development of the sequence. This strategy made it possible to reconstruct learning as a situated process and not merely as an isolated final outcome.

The combination of different sources responded to the logic of data triangulation aimed at strengthening the interpretative credibility of the qualitative analysis (Carter et al., 2014; Crowe et al., 2011; Tracy, 2010). In total, the analyzed corpus consisted of 97 meaning units with explanatory content about sound.

2.5. Data Analysis Procedure

Before describing the analytical procedure, Table 1 summarizes the main methodological elements of the study in order to facilitate the reading of the design, the data sources, and the type of treatment applied to the corpus.

Table 1. Summary of the methodological design and data analysis procedure.

Methodological Element	Description
General approach	Design-Based Research
Article design	Qualitative case study
Context	Public Primary Education school in Zaragoza, Spain
Participants	41 fifth-grade Primary Education students
Intervention	Eight-session STEAM sequence on sound
Data sources	Students' productions, observational records kept by the first author acting as teacher-researcher, and final product
Unit of analysis	Meaning unit
Analyzed corpus	97 meaning units
Type of analysis	Qualitative thematic content analysis
Purpose of frequency counts	Descriptive, not inferential

Source: Own elaboration.

The data analysis was aimed at reconstructing how students elaborated and transformed their explanations of sound throughout the sequence. Rather than classifying responses as correct or incorrect, the analysis focused on three complementary dimensions: (1) the explanatory model mobilized by the students, (2) the conceptual core underlying each explanation, and (3) the type of evidence used to support it. Particular attention was paid to how these dimensions evolved across the different stages of the didactic sequence.

To this end, a qualitative thematic content analysis was conducted, based on meaning units and guided by conceptual categories derived from the theoretical framework, the aim of the study, and the didactic focuses of the sequence (Nowell et al., 2017; Roberts et al., 2019; Shenton, 2004). The unit of analysis was defined as each discursive or productive fragment from the students that expressed an interpretable idea about the production, propagation,

or modification of sound. Short answers, justifications, comparisons, reformulations, and collective conclusions with explanatory content were included. Exclusively organizational teacher interventions and fragments that did not allow any model orientation to be inferred were not coded.

Coding was organized into three complementary dimensions. The first dimension corresponded to the orientation of the explanatory model mobilized by the students. Seven orientations were distinguished: non-modelling statement, phenomenological-descriptive model, substantialist model of sound, linear transmission model, mediated vibrational model, relational model of the sound phenomenon, and transferred relational model.

The second dimension referred to the conceptual core mobilized in each meaning unit. The following cores were considered: vibrational genesis of sound, propagation through a material medium, dependence of propagation on the medium, sound intensity, pitch, sound production, and transfer of the model to new situations.

The third dimension addressed the type of evidence used to support the explanations. Non-justified claims, observational evidence, comparative evidence, and experience-based inferences were differentiated.

The analytical procedure followed a sequential four-phase process designed to progressively move from data organization to thematic interpretation. First, the full corpus was read and segmented into meaning units. Second, each unit was coded according to the orientation of the model, the conceptual core mobilized, and the type of evidence used. Third, the codes were grouped by sequence block and classroom group in order to identify regularities, internal differences, and possible progressions. Finally, the results were organized into frequency matrices with a descriptive, non-inferential purpose, in order to make visible patterns of change, persistence, and reformulation in classroom explanations.

It should be noted that the corpus does not allow complete individual trajectories of all students to be reconstructed, since a substantial part of the evidence comes from aggregated classroom records and shared conclusions. Therefore, the inferences of the study are mainly situated at the level of the progression of collective classroom discourse and the evolution of the explanations that emerged during the implementation.

2.6. Methodological Rigor and Ethical Considerations

To strengthen the methodological quality of the study, criteria of credibility, internal coherence, analytical transparency, thick contextual description, and researcher reflexivity were considered (Shenton, 2004; Tracy, 2010). Credibility was supported by sustained observation throughout the sequence and by triangulation between students' productions, observational records, and the final product, which made it possible to contrast interpretations through diverse and complementary evidence (Carter et al., 2014; Shenton, 2004; Tracy, 2010).

Internal coherence was ensured through the alignment between the aim of the study, the qualitative case study design, the construction of the corpus, and the analytical procedure. Analytical transparency was strengthened by explicitly defining the segmentation criteria, the coding dimensions, the phases of analysis, and the relationship between evidence, categories, and interpretation (Nowell et al., 2017; Roberts et al., 2019). Likewise, the description of the context, the didactic sequence, and the sources of information made it possible to situate the results within the specific conditions of the implementation.

Since the sequence was designed and implemented by the author, the dual role of teacher-researcher was explicitly acknowledged. This position provided close access to the classroom process, but it also required a reflexive stance regarding the influence of pedagogical decisions, teacher mediation, and proximity to the field on the production and interpretation of the data (Berger, 2015; Dwyer & Buckle, 2009). Reflexivity was therefore

understood as a necessary methodological condition of the study, rather than as an external element of the research process.

From an ethical point of view, the treatment of information followed criteria of anonymization, academic use of data, and protection of the identity of the students and the school. Individual references were presented in aggregated or coded form, ensuring the confidentiality of the participants. In addition, the implementation had the authorization of the school and followed the corresponding information and consent procedures for the academic use of the data generated in the classroom.

3. Results

3.1. Global Distribution of Explanatory Model Orientations

The analysis of the corpus made it possible to identify different explanatory model orientations mobilized by the students throughout the didactic sequence. A total of 97 meaning units were analyzed, derived from students' oral and written productions, observational records kept by the teacher-researcher, and evidence linked to the final product. In accordance with the qualitative approach of the study, these units were not interpreted as independent individual answers or as performance indicators, but as evidence of the types of explanations that emerged in the collective classroom discourse.

The global distribution showed the presence of seven explanatory model orientations, ranging from non-modelling statements or explanations centred on immediate perception to relational and transferred explanations. To facilitate the interpretation of the results, these orientations were grouped into two broader levels: initial or less elaborated models (M0–M3) and models closer to the school scientific model of sound (M4–M6). The first group included non-modelling statements, phenomenological-descriptive explanations, substantialist interpretations of sound, and linear transmission models. The second group included the mediated vibrational model, the relational model of the sound phenomenon, and the transferred relational model.

Overall, the more elaborated models (M4–M6), corresponding to explanations closer to the school scientific model of sound, accounted for 55 of the 97 coded units (56.7% of the corpus). By contrast, the initial or less articulated models (M0–M3) accounted for 42 units (43.3%). As shown in Table 2, this distribution suggests that, when the didactic sequence is considered as a whole, students more frequently produced relational explanations that integrated key conceptual elements such as vibration, the material medium, sound production, and the transfer of the model to new situations. This overall pattern is consistent with the aim of the sequence to promote progressively more elaborated scientific explanations.

Table 2. Global distribution of explanatory model orientations.

Group of Model Orientations	Included Orientations	Number of Units	Percentage
Initial or less elaborated models	M0. Non-modelling statement; M1. Phenomenological-descriptive model; M2. Substantialist model of sound; M3. Linear transmission model	42	43.3%
More elaborated models	M4. Mediated vibrational model; M5. Relational model of the sound phenomenon; M6. Transferred relational model	55	56.7%
Total		97	100%

Source: Own elaboration.

Within this distribution, the relational model of the sound phenomenon was the most frequent orientation, with 31 units, representing 32.0% of the corpus. It was followed by the phenomenological-descriptive model and the mediated vibrational model, both with 19 units, representing 19.6% each. As shown in Table 3, these three orientations accounted for the largest identifiable proportions of the corpus and help to understand the coexistence of descriptive and more elaborated explanations throughout the sequence.

Table 3. Most frequent explanatory model orientations in the corpus.

Explanatory Model Orientation	Number of Units	Percentage	Interpretation Within the Learning Process
Relational model of the sound phenomenon (M5)	31	32.0%	Students coordinated several elements of the sound model, such as vibration, propagation, medium, and sound properties.
Mediated vibrational model (M4)	19	19.6%	Students began to explain sound through vibration and mediation, especially in relation to propagation through materials.
Phenomenological-descriptive model (M1)	19	19.6%	Students described what they perceived or observed, but without fully articulating an explanatory model

Source: Own elaboration.

3.2. Evolution of Explanatory Models Across the Didactic Sequence

The analysis by sequence blocks made it possible to identify changes in the weight of the different explanatory model orientations throughout the intervention. This analysis is especially relevant because the global distribution combines evidence produced at different moments of the sequence and, by itself, does not fully show the internal progression of the process.

In the first block, focused on sound production, vibration as the origin of sound, and an initial approach to pitch and intensity, less elaborated orientations were predominant. Many explanations were based on immediate perceptual experience and on descriptive formulations. In this phase, students tended to describe what they heard or observed, but did not always relate these observations to an articulated explanatory model. These responses were mainly associated with phenomenological-descriptive orientations and, in some cases, with statements that did not yet show a clear modelling function.

Figure 1 illustrates several tasks carried out during the first block of the didactic sequence. These tasks were designed to promote direct exploration of sound production through manipulation, observation, and classroom discussion. Their purpose was twofold: to provide students with an initial experience of the phenomenon and to make visible their first explanatory orientations, especially those based on what they heard, observed, or associated with sound generation. In this sense, they offered an entry point for identifying initial explanations and for progressively guiding students towards more articulated relationships between sound production and vibration. These initial activities therefore established the baseline from which subsequent conceptual development could be interpreted.

In the second block, focused on sound propagation through different material media, a shift towards more elaborated explanations was identified. Although initial formulations were still present, the mediated vibrational model increased in relevance. This was especially visible in tasks in which students had to explain sound transmission through solids, confined air, water, or contrasting situations between different media. In these tasks, students' explanations began to include relationships between vibration, transmission, and material conditions, rather than remaining limited to the description of perceptual effects.

Figure 2 shows examples of tasks implemented during the second block of the sequence. These tasks were designed to promote comparison between different propagation conditions and to encourage students to move beyond explanations based only on immediate perception. From an analytical perspective, they were relevant because they required students to relate observed changes in sound transmission to the material conditions involved, thereby supporting the emergence of mediated vibrational explanations. Overall, this block marked the transition from predominantly descriptive accounts towards explanations that increasingly incorporated causal relationships between vibration and sound propagation.



Figure 1. Activities from the first block of the didactic sequence focused on sound production and initial explanatory orientations. Note: The image shows classroom activities used to elicit students' initial ideas about sound production through direct exploration, observation, and discussion.



Figure 2. Activities from the second block of the didactic sequence focused on sound propagation and mediated vibrational explanations. Note: The activities were used to support students' transition from perceptual descriptions towards explanations based on the relationships between vibration, transmission, and material media.

In the third block, focused on application, sound production, and conceptual transfer through the construction of the bottle xylophone, the initial orientations disappeared from the coded units. In this final phase, relational and transferred models became clearly predominant. The tasks required students to apply previous ideas to a new situation, particularly when explaining how the amount of water, air vibration, tuning, and pitch variation were related in the functioning of the final product.

Figure 3 shows examples of tasks implemented during the third block of the sequence. These tasks were designed to promote the application of the sound model to a new sound-producing situation through the construction and exploration of a bottle xylophone. From an analytical perspective, they were relevant because they required students to connect previously addressed ideas about sound production, vibration, material conditions, and pitch variation, thereby supporting the emergence of relational and transferred explanations. These findings suggest that the final activities encouraged students to apply the sound model beyond the original learning situations, demonstrating an increasing level of conceptual integration and transfer.



Figure 3. Activities from the third block of the didactic sequence focused on conceptual transfer through the bottle xylophone. Note: The activities supported the emergence of relational and transferred explanations by requiring students to apply the sound model to the construction and functioning of the final product.

This evolution is summarized in Figure 4. In the first block, initial models (M0–M3) represented 59.5% of the coded units. In the second block, they represented 54.1%. In the third block, these initial orientations were no longer identified in the coded units, while the relational and transferred models (M5–M6) reached 91.3% of the units. Therefore, the results show a progressive reduction of initial or less articulated explanations and a final predominance of relational and transferred explanations.

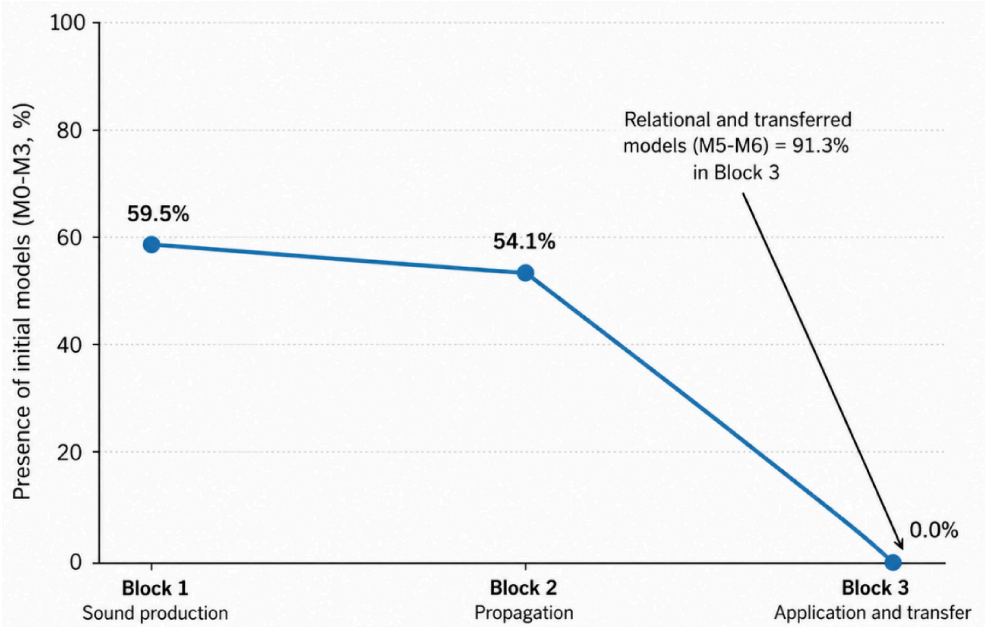


Figure 4. Evolution of Explanatory Model Orientations Across the Didactic Sequence. Note: Percentages are reported only for the categories explicitly quantified in the analyzed matrices. The figure is intended to show the main progression pattern rather than a full cross-tabulation of all explanatory model orientations.

3.3. Progression from Initial to More Elaborated Explanations

The comparison between the beginning and the end of the sequence shows a clear change in the nature of students' explanations. During the first block, many meaning units were centered on what students perceived, heard, or observed. These explanations were often descriptive and did not always include explicit relationships between the origin of sound, vibration, propagation, and the material medium. By contrast, in the final block, students' explanations were more frequently relational and applied to a new situation.

This progression was not interpreted as a linear or homogeneous individual change, since the corpus does not allow complete individual trajectories to be reconstructed. However, it does show a transformation in the collective classroom discourse. Initial explanations did not disappear immediately, but their relative presence decreased as the sequence progressed. At the same time, explanations closer to the school scientific model of sound became increasingly relevant, especially in tasks requiring comparison, justification, and application. Table 4 summarizes the main changes observed between the initial and final tendencies of the sequence.

Table 4. Main changes observed before and after the implementation of the sequence.

Analytical Dimension	Initial Tendency	Final Tendency	Evidence of Improvement
Explanatory orientation	Predominance of descriptive, phenomenological, or weakly articulated explanations	Predominance of relational and transferred explanations	Initial models (M0–M3) decreased from 59.5% in Block 1 to 0.0% in Block 3
Role of vibration	Vibration was not always explicitly connected to sound production	Vibration became more explicitly present in students' explanations	Students increasingly related sound production to vibrational processes
Role of material medium	Propagation was initially described in perceptual or linear terms	Propagation was increasingly linked to the need for a material medium	The mediated vibrational model became more relevant in Block 2

Table 4. *Cont.*

Analytical Dimension	Initial Tendency	Final Tendency	Evidence of Improvement
Relationship between sound properties	Pitch and intensity were initially described through everyday perceptual language	Students' explanations began to connect sound variation with physical and material conditions	Final explanations included relationships between amount of water, air vibration, tuning, and pitch
Transfer to new situations	Explanations were mainly linked to the immediate activity	Students used the model to explain the bottle xylophone	Relational and transferred models (M5–M6) reached 91.3% in Block 3
Use of evidence	More frequent use of non-justified claims or simple descriptions	Greater use of observation, comparison, and inference	Students' explanations increasingly drew on observation, comparison, and inference.

Source: Own elaboration.

3.4. Use of Evidence and Emergence of Conceptual Transfer

In addition to the evolution of explanatory model orientations, the analysis also showed changes in the type of evidence used by students to support their explanations. In the first moments of the sequence, non-justified claims and simple descriptions of what happened were more frequent. These responses often referred to perceptual experience but did not always include explicit reasoning about why the phenomenon occurred.

As the sequence progressed, explanations increasingly incorporated observational and comparative evidence. This was particularly visible in activities based on comparison between different media or experimental conditions. In these cases, students began to support their explanations by referring to what had been observed, what had changed between situations, or what could be inferred from the contrast between materials.

The clearest evidence of this progression appeared in the final block, especially in the activities related to the construction and explanation of the bottle xylophone. In this phase, some responses no longer reproduced isolated vocabulary, but applied relationships constructed during the sequence to explain a new situation. Students had to connect sound production, amount of water, air vibration, tuning, and pitch variation in order to explain how the instrument worked. This type of response was coded as a transferred relational model when the explanation showed application of the model beyond the initial experimental context. This evolution in the use of evidence is synthesized in Table 5.

Table 5. Evolution in the use of evidence throughout the sequence.

Moment of the Sequence	Type of Explanation Commonly Observed	Type of Evidence Used	Analytical Interpretation
Initial activities	Descriptions of what students heard or observed	Non-justified claims and direct perceptual references	Students recognized features of the phenomenon but did not always explain their causes
Intermediate activities	Explanations based on comparison between situations	Observational and comparative evidence	Students began to relate changes in sound to changes in material or experimental conditions
Final activities	Relational explanations applied to the bottle xylophone	Experience-based inferences and conceptual transfer	Students used the model as a tool to explain a new sound-producing situation

Source: Own elaboration.

Overall, the results indicate that the sequence was associated not only with a change in the conceptual content of students' explanations, but also with a shift in the way they justified them. The progression from descriptive or weakly justified statements towards explanations supported by observation, comparison, and inference suggests that students gradually began to use the model of sound as a tool for interpreting new situations.

4. Discussion

The findings summarized in Table 6 provide evidence of a progressive transformation in students' explanatory models of sound. The following discussion interprets these results in relation to previous research and examines their implications for model-based learning, STEAM education, and the teaching of sound in Primary Education.

Table 6. Overview of the Main Findings Supporting the Discussion.

Main Finding	Empirical Basis	Meaning for the Study
More elaborated models were globally more frequent than initial models	M4–M6 represented 56.7% of the corpus; M0–M3 represented 43.3%	The sequence generated a corpus in which relational explanations had greater weight than initial explanations
Initial explanations decreased across the sequence	M0–M3 represented 59.5% in Block 1, 54.1% in Block 2, and 0.0% in Block 3	The collective classroom discourse moved away from descriptive or weakly articulated explanations
Relational and transferred explanations predominated at the end	M5–M6 represented 91.3% of the coded units in Block 3	The final tasks favoured the use of the sound model in new explanatory contexts
The use of evidence became more elaborated	Observational, comparative, and inference-based explanations increased across the sequence	Students progressively justified their explanations through evidence generated in classroom activities
The bottle xylophone acted as a transfer task	Final explanations connected water level, air vibration, tuning, and pitch variation	The final product made visible the application of the model beyond isolated experiments

Source: Own elaboration.

The findings indicate a progressive reorganization of students' explanations, moving from perception-based, descriptive, or weakly articulated formulations towards more relational explanations closer to the school scientific model of sound. This progression was particularly evident in the final block of the sequence, where initial models (M0–M3) were no longer identified in the coded units and relational or transferred models (M5–M6) reached 91.3% of the corpus. These findings suggest that the sequence created favorable conditions for students to coordinate sound production, vibration, propagation through material media, and pitch variation within increasingly articulated explanatory frameworks. Beyond confirming previous research, these findings extend model-based learning theory by illustrating how a structured STEAM-based sequence can progressively support the coordination of conceptual elements involved in students' explanations of sound. Rather than viewing modelling as the acquisition of isolated scientific concepts, the present study highlights how carefully sequenced classroom activities can promote the gradual construction, refinement, and transfer of explanatory models in authentic educational contexts. At the same time, these findings should be interpreted in light of the contextual nature of the study. Although the following discussion highlights the educational implications of the results, they should be understood as situated evidence generated in a specific classroom context. Consequently, factors such as classroom interactions, teacher mediation, and individual differences among students may have influenced the evolution of the explanatory

models observed. These methodological limitations are discussed in greater detail later in this section.

This progression should not be interpreted as an immediate replacement of previous ideas by stable scientific conceptions. Rather, the findings point to a gradual process of reorganization in collective classroom discourse. This distinction is important because learning about sound does not simply involve adding scientific vocabulary to students' everyday descriptions. It requires students to reconstruct relationships that explain why sound is produced, how it propagates, and how its properties vary. From this perspective, the findings are consistent with model-based approaches to science education, which understand learning as the construction, testing, revision, and application of explanatory models rather than as the acquisition of isolated concepts or definitions (Carroll & Park, 2026; Li et al., 2025; Windschitl et al., 2008).

The initial explanations identified in the first block were consistent with difficulties widely documented in previous research on sound learning. Several responses were centered on what students heard, perceived, or observed, without explicitly connecting these experiences to an explanatory model based on vibration and propagation. This finding aligns with studies showing that students often interpret sound through everyday perceptual experience and may conceive it as a material entity, an object, or something that moves independently of the medium (Eshach & Schwartz, 2006; Eshach et al., 2018; Hrepic et al., 2010). It also supports the idea that everyday familiarity with sound does not guarantee scientific understanding, especially when students have to reason about non-visible processes such as vibration, transmission, and the role of the material medium (Rico et al., 2021; Veith, 2023).

One of the main contributions of this study is the identification of a transition from descriptive explanations to mediated vibrational and relational explanations. This transition was especially visible in the second block, focused on sound propagation through different media. The comparison between solids, air, water, and vacuum-like situations appeared to encourage students to move beyond explanations based only on perceptual effects and begin relating sound transmission to material conditions. This result is relevant because the role of the medium is one of the central conceptual obstacles in the construction of the school scientific model of sound (J. P. Costa et al., 2024; Rico et al., 2021; Veith, 2023). The findings suggest that comparison between different propagation conditions may help students make inferable what is not directly visible, thereby supporting the transition from description to explanation.

In this sense, the sequence did not merely provide hands-on experiences. Its didactic value seems to lie in the way practical exploration was organized as a context for comparison, justification, and model construction. This distinction is important in Primary Education, where manipulative activities are often assumed to be educationally valuable by themselves. The findings of this study suggest that manipulation alone is not enough. What appears to have supported the progression of students' explanations was the articulation between action on materials, observation of effects, comparison between situations, and guided reconstruction of explanations. This interpretation is consistent with research emphasizing that inquiry and experimentation acquire greater educational value when they are connected to processes of interpretation and conceptual modelling (Dah et al., 2024; Premthaisong & Srisawasdi, 2024; van Eijck et al., 2025).

The improvement observed was not limited to the conceptual content of students' explanations. A relevant shift was also identified in the way students used evidence to support their reasoning. At the beginning of the sequence, explanations were more frequently based on unelaborated descriptions or non-justified claims. As the sequence progressed, students increasingly referred to observations, comparisons between experimental condi-

tions, and inferences grounded in classroom experience. This change suggests that learning about sound involved not only naming concepts such as vibration, propagation, pitch, or intensity, but also learning to justify why a given explanation was plausible in relation to the evidence generated in class. Therefore, the sequence appears to have supported both conceptual and epistemic dimensions of learning. This point is particularly relevant because school scientific modelling requires students to construct explanations that are not only conceptually more sophisticated, but also better supported by evidence. The movement from "what I hear" or "what I see" towards "what this situation allows me to infer" marks an important shift in students' participation in scientific practices. In this study, the use of evidence became more elaborated when students were required to compare media, identify differences between conditions, and explain the functioning of the bottle xylophone. This finding aligns with studies that emphasize the importance of engaging students in scientific practices such as observing, comparing, arguing, justifying, and revising explanations (Dah et al., 2024; Muñoz et al., 2020; Urdanivia Alarcon et al., 2023; Windschitl et al., 2008; Zamalloa et al., 2025).

The emergence of transferred relational explanations in the final block provides further support for this interpretation. The construction and explanation of the bottle xylophone required students to apply previously developed relationships to a new sound-producing situation by coordinating water level, air vibration, sound production, and pitch variation. The instrument therefore functioned not only as a final product but also as a didactic tool for integrating physical and musical dimensions through scientific explanation. Although the study does not demonstrate stable conceptual transfer at the individual level, the emergence of transfer-oriented explanations suggests that the didactic sequence supported the collective application of the sound model in a new context. These findings indicate that final production tasks can promote transfer and model-based reasoning when they are explicitly connected to conceptual goals.

From the perspective of STEAM education, the findings offer a nuanced contribution. Although the study does not isolate the effect of the artistic component or demonstrate that STEAM approaches are inherently more effective than other didactic designs, it shows that science–music integration can be educationally meaningful when both disciplines address a shared explanatory problem. In this study, science provided the conceptual tools for understanding sound, while music offered authentic contexts in which students produced, modified, compared, and explained the phenomenon. Consequently, the value of the STEAM approach lay not in the mere inclusion of music, but in its meaningful integration into the construction and application of scientific explanations, responding to current calls for more coherent interdisciplinary approaches in STEAM education (Chappell et al., 2025; Yim et al., 2025).

This finding is especially important for Primary Education. Sound is both a physical phenomenon and an everyday musical experience. For this reason, it offers a particularly fertile context for designing integrated proposals in which disciplinary boundaries are crossed without losing conceptual rigor. The findings suggest that science–music integration may be especially productive when musical practice is not treated as a final ornament, but as a context for generating evidence, posing questions, testing relationships, and making scientific models functional. This interpretation is consistent with studies that defend the potential of science–music integration when it contributes to meaning-making rather than functioning as a superficial contextualization of science learning (Blanco-García et al., 2025; Bravo-Fuentes et al., 2025; Eramo et al., 2025; Filipe et al., 2024; Soto & Porflitt, 2024).

The findings also have several implications for teaching sound in Primary Education. First, they suggest that sound should be approached as a phenomenon to be progressively modelled, rather than as a set of definitions to be transmitted. Concepts such as vibration,

medium, pitch, and intensity may remain fragmented if they are not connected through inquiry, comparison, and explanation. Second, the findings highlight the importance of designing tasks that make invisible processes inferable through observable effects. Since vibration and propagation are not always directly perceptible, students need situations that help them connect what they observe with what they infer. Third, the study points to the didactic value of synthesis tasks in which students must apply the model to a new situation. In this regard, the construction of an instrument can become a powerful resource when it is explicitly linked to scientific explanation.

At the methodological level, this study contributes to science education research by offering a qualitative reconstruction of the evolution of explanatory models in an ordinary classroom context. Instead of focusing only on misconceptions or final achievement, the analysis examined intermediate forms of reasoning and the movement between different explanatory orientations. This approach makes it possible to capture processes of partial construction, persistence, reformulation, and transfer that may remain hidden in more product-oriented evaluations. It also allows the study to describe how the model becomes progressively functional in classroom discourse, which is particularly relevant in research on conceptual change and modelling.

However, the methodological design also defines the scope of the findings. Since part of the evidence comes from aggregated classroom records and shared conclusions, the findings mainly describe the progression of collective classroom discourse and cannot be used to establish causal effects or complete individual learning trajectories. In addition, the study involved two fifth-grade groups from a single school, which limits the transferability of the findings to other educational contexts. Moreover, the first author's dual role as teacher-researcher may have influenced both the implementation of the sequence and the interpretation of the data. This does not invalidate the study, but it requires understanding the findings as situated evidence generated in a specific educational context. Future research should therefore incorporate additional implementations, more systematic individual data collection, and longitudinal follow-up to examine the stability and transferability of the observed progression.

Overall, the findings support the idea that teaching sound in Primary Education can be organized as a process of school scientific modelling. The sequence was associated with a gradual movement from descriptive and perception-based explanations towards more relational and transferable ways of explaining sound. This progression was especially visible when students compared different media, justified their interpretations through evidence, and applied the model in the construction of the bottle xylophone. Therefore, the study contributes situated evidence on how a STEAM-based sequence can support the construction of the school scientific model of sound, provided that the integration between science and music is conceptually articulated, didactically intentional, and oriented towards explanation.

5. Conclusions

This study analyzed how fifth-grade Primary Education students constructed and transformed their understanding of sound throughout a STEAM-based didactic sequence implemented in a real classroom context. The findings show a progressive movement in collective classroom discourse from descriptive, perception-based, or weakly articulated explanations towards more relational and transferable explanations closer to the school scientific model of sound.

The main contribution of this study to the literature lies in providing situated evidence of how a STEAM-based modelling sequence can support the progressive construction and application of the school scientific model of sound in Primary Education. Rather than

simply documenting conceptual change, the study illustrates how inquiry, comparison between media, evidence-based justification, and the construction of a final product can work together to support students' scientific modelling processes. In this way, the study contributes to current research on model-based science education by providing a detailed account of how explanatory models can be progressively constructed and applied in authentic classroom contexts.

The findings also suggest that science–music integration can be pedagogically meaningful when both dimensions are articulated around the same explanatory problem. In this study, music was not treated as an additional motivational resource, but as a context for producing, modifying, comparing, and explaining sound. The construction of the bottle xylophone was particularly relevant because it provided a synthesis task in which students could apply the model of sound to a new and functional situation.

These conclusions should be interpreted within the limits of the study. The research was conducted as a qualitative case study in a specific school context, and the corpus does not allow complete individual learning trajectories to be reconstructed. Therefore, the findings should not be read as statistical evidence of generalizable effectiveness, but as situated evidence on how students' explanations can evolve during a STEAM-based modelling sequence.

Future research should extend the implementation to other educational contexts, incorporate more systematic individual data collection, and analyse the stability of students' explanations over time. It would also be valuable to compare different forms of science–music integration in order to better understand which design features most strongly support the construction and transfer of the school scientific model of sound.

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Data Availability Statement: The data supporting the findings of this study are not publicly available due to privacy and ethical restrictions, as they include anonymised classroom records and student productions from minors. Aggregated data and coding information may be made available from the corresponding author upon reasonable request, where compatible with the consent conditions and applicable data protection requirements.

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