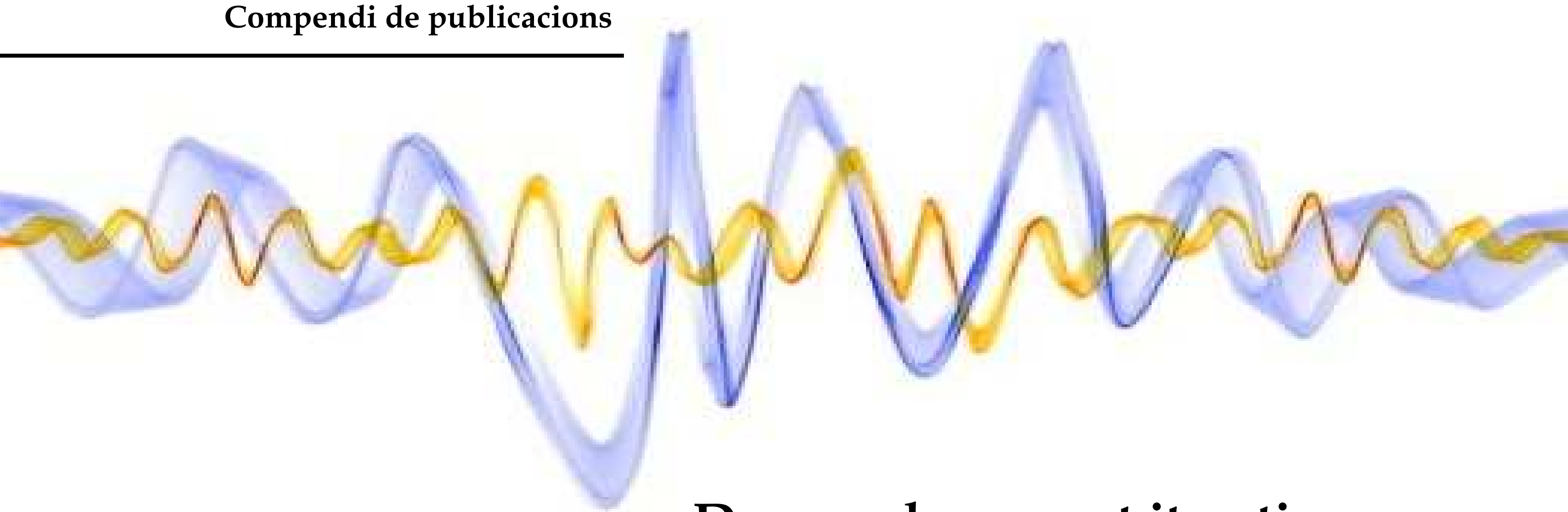
Tesi doctoral

Compendi de publicacions



Desenvolupament iteratiu d'una seqüència d'ensenyament i aprenentatge sobre Propietats Acústiques dels Materials

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A Miguel, Isabel, Luis y Alberto,

por quererme tanto,

por ser el motor de mi vida.

Presentació

Aquesta tesi doctoral està estructurada seguint les directrius de la normativa per la presentació de tesis doctorals com a compendi de publicacions, aprovada per la Comissió de Doctorat de la Universitat Autònoma de Barcelona i regulada pel RD 1393/2007.

Seguint la normativa que regula el format de presentació de tesi doctoral per compendi de publicacions, hem estructurat aquest treball en tres seccions principals:

- Secció 1. Introducció i justificació de la unitat temàtica de la tesi
- Secció 2. Publicacions que formen part del compendi de la tesi
- Secció 3. Resum global dels resultats i conclusions finals

Per aquesta tesi, s'aporten quatre articles originals que segueixen una mateixa línia d'investigació, la recerca basada en el disseny d'innovacions per a l'ensenyament i aprenentatge de ciències. Tres d'aquests quatre articles han estat aprovats per la Comissió d'Estudis de Postgrau el dia 16 de maig de 2012 (veure carta Annex 1) per ser presentats com a tesi doctoral per compendi de publicacions i s'adjunten en la llengua i format original de publicació.

- Hernández, M. I., Couso, D., & Pintó, R. (2011). The Analysis of Students' Conceptions as a Support for Designing a Teaching/Learning Sequence on the Acoustic Properties of Materials. *Journal of Science Education & Technology*. doi 10.1007/s10956-011-9358-4.
- Hernández, M. I., Couso, D., & Pintó, R. (2011). Teaching acoustic properties of materials in secondary school: Testing sound insulators. *Physics Education*, *46(5)*, 559-569.
- Hernández, M. I., & Pintó, R. (en premsa). The process of iterative development of a teaching/learning sequence on acoustic properties of

materials. A D. Psillos & P. Kariotoglou (Eds.), *Iterative design of teaching-learning sequences: introducing the science of materials in European schools*. The Netherlands: Springer Editorial.

Tal com ha resolt la Comissió d'Estudis de Postgrau, el quart article o manuscrit forma part de la tesi com a annex (veure Annex 2) tot i que no es troba encara publicat ni acceptat per a publicació.

- Hernández, M. I., Couso, D., & Pintó, R. Refining design principles of a teaching-learning sequence with a model-based inquiry approach: Contributions from the analysis of students' learning pathways.

La formació de l'autora de la present memòria per optar al títol de tesi doctoral ha comptat amb el suport econòmic de les següents ajudes personals a l'investigador:

- Beca de Formación de Profesorado Universitario (FPU) adscrita al Centre de Recerca per a l'Educació Científica i Matemàtica (CRECIM), Universitat Autònoma de Barcelona. Ref.: AP2007-01560. Període: setembre/2008 – agost/2012.
- Ayuda para estancia breve en el extranjero, a la University of Washington (Seattle, WA, USA), a personal investigador en formación del Programa Nacional de Formación de Profesorado Universitario. Període: setembre/2010 – desembre/2010.

Les publicacions que constitueixen aquesta tesi doctoral per compendi de publicacions han estat realitzades amb el suport del següent ajut a la recerca:

- Materials Science Project (University-school partnerships for the design and implementation of research-based ICT-enhanced modules on Material Properties), finançat per la Comissió Europea. DG Research, dins del programa Science & Society. Ref.: SAS6-CT-2006-042942. Període: 2007 – 2010.

Agraïments

Arribats a aquest punt del camí de la meva encara incipient carrera professional, és moment de fer balanç i valorar tot el suport i ànim rebuts al llarg d'aquesta senda anomenada tesi doctoral, que ha arribat a ser el que és gràcies a un bon nombre de gent.

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Una mica més lluny d'aquest món acadèmic però igual d'influents en la meva trajectòria personal han estat tots els familiars i els amics i amigues que sempre han confiat en mi i que no han deixat de donar-me ànims i de recordar-me la quantitat de coses importants que ens envolten i per les quals val la pena continuar sempre endavant. Gràcies a tots ells i elles per acompanyar-me en

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So it's really in retrospect that you see things.
You don't always see them all the time.

Rosalind Driver

Defining an Identity: The Evolution of
Science Education as a Field of Research

My final message to those who would like to be involved in curriculum development is: 'be lucky'. Do your best to live in interesting times.

Jon Ogborn

Designing Theory-Based Teaching-Learning
Sequences for Science Education

A fora, el món sembla enorne,
Aquí, el futur sembla immens.

David Jou

El profesor. Cinc poemes sobre l'ensenyament
(Aules buides)

Resum

La present tesi doctoral explora diversos aspectes del procés de desenvolupament iteratiu d'una seqüència per a l'ensenyament i aprenentatge sobre propietats acústiques dels materials. Les diferents publicacions que formen part del compendi de la tesi posen en relleu les diferents etapes d'aquest procés: disseny, implementació, avaluació, refinament i contribució als principis de disseny. Identificar quines accions es duen a terme en cadascuna d'aquestes etapes i amb quins criteris i metodologies és el focus d'aquesta tesi.

Aquesta recerca parteix de la convicció de que és possible promoure l'aprenentatge d'aquest contingut amb alumnes de secundària, integrant coneixement generat per la recerca i l'experiència dels professors, establint lligams entre els àmbits de la innovació i la recerca. Aquesta tasca, però, està lluny de ser òbvia, ja que interpretar i implementar eficientment els resultats de la recerca a la pràctica educativa no és immediat. És per això que aquesta tesi es centra en analitzar el desenvolupament iteratiu d'una seqüència d'ensenyament i aprenentatge per millorar la qualitat de la mateixa, entenent per qualitat una sèrie de criteris avaluables com la validesa, la utilitat i l'eficàcia.

Per portar a terme aquest estudi, es van analitzar les observacions d'aula i les produccions escrites de diferents poblacions d'alumnes de 4t d'ESO al llarg de la implementació de cada versió de la seqüència d'ensenyament i aprenentatge durant tres cursos consecutius. També es van tenir en compte les notes de les reunions del grup de dissenyadors del material, del qual formaven part investigadors en didàctica de les ciències i professors de secundària que van implementar el material a les seves classes. L'anàlisi d'aquest conjunt de dades ens ha permès caracteritzar el procés de refinament de la seqüència i descriure la dinàmica de desenvolupament de models conceptuals per part dels alumnes, tot avaluant la influència de determinades activitats de la seqüència dissenyada.

Abstract

The present doctoral dissertation explores diverse aspects of the process of iterative development of a teaching – learning sequence on the acoustic properties of materials. The different publications that are part of the compendium of the thesis focus on different stages of this process: design, enactment, evaluation, refinement and contribution to the design principles. Identifying which actions are carried out in each of these stages and which criteria and methods are used is the focus of this thesis.

This research study is based on the conviction that it is possible to promote secondary school students' learning of this content, integrating research-generated knowledge and teachers' experience, establishing links between the arenas of innovation and research. Nevertheless, this task is far from being obvious since interpreting and effectively implementing research results in educational practice is not immediate. For this reason, this thesis is focused on analysing the iterative development of a teaching – learning sequence in order to enhance its quality, understanding it as a set of assessable criteria such as validity, practicality and effectiveness.

With the purpose of carrying out this study, we analyzed classroom observations and written productions from different samples of 15-16 year-old students throughout the enactment of each version of the teaching – learning sequence during three consecutive academic years. We also took into account the notes taken during the meetings of the designer group, which was formed by researchers in science education and secondary school teachers who implemented the material in their classes. The analysis of these data allowed characterizing the process of refinement of the teaching sequence and describing the dynamics of students' development of conceptual models, evaluating the influence of certain activities of the designed teaching sequence.

Taula de continguts

Llista de figures

Llista de taules

SECCIÓ I. INTRODUCCIÓ

Justificació de la recerca

Objectius de la recerca

Justificació de la unitat temàtica de la tesi

Capítol 1

Justificació de la recerca

El compendi de publicacions que forma part d'aquesta tesi doctoral explora diversos aspectes del procés de desenvolupament iteratiu d'una innovació per a l'ensenyament i aprenentatge d'un contingut específic de ciències. Les diferents publicacions posen en relleu les diferents etapes d'aquest procés de desenvolupament iteratiu d'una innovació. Quines accions es duen a terme en cadascuna d'aquestes etapes i amb quins criteris i metodologies és el focus d'aquesta tesi.

La justificació d'aquesta recerca requereix abordar els següents aspectes:

- La importància del desenvolupament iteratiu d'innovacions
- L'interès de les seqüències d'ensenyament i aprenentatge com a producte i com a activitat de recerca empírica
- La rellevància del contingut de ciències específic de les propietats acústiques dels materials

Al llarg d'aquesta secció, s'analitzaran cadascun d'aquests aspectes amb la intenció de justificar la rellevància d'aquesta recerca per a l'educació científica.

1.1. Per què parlem de desenvolupament iteratiu?

... developmental research deals essentially with questions like
'how to teach X' or 'how to teach X better'.
Piet Lijnse (2003, p. 12)

Lijnse (1995) introduí en l'àmbit de la didàctica de les ciències el terme *recerca sobre el desenvolupament*, descrivint-lo com un "procés cíclic de reflexió teòrica, anàlisi conceptual, desenvolupament curricular a escala reduïda i recerca d'aula sobre la interacció entre processos d'ensenyament i aprenentatge" (p. 192). Duit (2006, p. 752) utilitzà els mateixos termes per parlar del "procés cíclic de reconstrucció educativa". Autors com van den Akker (1999, p. 8) consideren que aquest tipus de procés iteratiu "d'aproximació successiva" a la intervenció "ideal" és necessari per tal de solucionar molts problemes de la pràctica educativa. Tant els anteriors autors com els que formen part del col·lectiu anomenat Design-based Research Collective (2003, p. 5) coincideixen en que qualsevol *recerca basada en el disseny* té com a tret característic que "el desenvolupament i la recerca progressen a través de continus cicles de disseny, implementació, anàlisi i redisseny".

Per tal d'evitar ambigüitats, aclarim aquí el significat atribuït al llarg d'aquest treball de tesi a cadascun dels termes clau abans mencionats. I és que tradicionalment s'acostuma a parlar de la recerca, del desenvolupament i de la innovació com a processos diferents que guarden entre sí certes relacions. Segons Aho (2006), la diferència entre recerca i innovació en l'àmbit empresarial es basa en que la primera és el procés "d'invertir diners per obtenir coneixement", mentre que la segona consisteix en "invertir coneixement per obtenir diners". Si bé aquesta distinció pot ser pertinent en camps com els de la ciència i la tecnologia, necessitem traduir alguns termes a altres àmbits com el de l'educació científica. En aquest sentit, ens sembla més adient la distinció que estableixen Jadad i Lorca (2007), els quals descriuen la recerca com "la inversió de recursos per a obtenir coneixement, i la innovació com la inversió de coneixement per a obtenir valor". Aquest valor pot significar un positiu retorn social o una millor manera d'adaptar-nos als canvis i necessitats que constantment se'ns presenten en l'àmbit educatiu.

En termes generals, entenem la *recerca* sobre l'educació científica com un procés d'indagació planificada que pretén construir nous coneixements i comprendre millor una realitat educativa determinada. D'altra banda, el terme *desenvolupament* fa referència a l'aplicació dels resultats de recerca en el disseny i/o millora de materials, productes o propostes educatives, que al seu torn implica sovint noves recerques sobre el propi procés de desenvolupament. Finalment, considerarem com a *innovació* tot aquell resultat d'un ús creatiu d'idees, mètodes o productes ja existents que suposi una solució a un problema donat o un avanç o millora substancial pels usuaris de la mateixa respecte als materials, mesures o propostes ja existents. Una innovació, però, no sempre és el resultat d'una recerca (Escorsa i Valls, 2003).

Al llarg d'aquest treball de tesi, el *desenvolupament iteratiu* es considera un procés que integra innovació i recerca, i que segueix un enfocament cíclic de disseny, implementació, avaluació o anàlisi i refinament o redisseny d'una innovació educativa.

Un cop especificats i definits alguns dels termes utilitzats al llarg d'aquest treball, ara convindria especificar les motivacions que ens han conduït a dur a terme el desenvolupament iteratiu d'una innovació educativa. En general, qualsevol desenvolupament de materials o propostes per a l'ensenyament de les ciències sol iniciar-se a partir de la identificació - i propòsit de superació - d'algun problema, mancança o necessitat de l'ensenyament i aprenentatge de les ciències, com poden ser:

- Una significativa manca d'excel·lència en els nivells de competència científica entre l'alumnat de 15 anys, així com una important fracció d'alumnat en els nivells de competència més baixa - tal com mostren els resultats a Espanya de comparacions internacionals, com les proves PISA 2009 (OCDE, 2010).
- Un preocupant declivi del nombre d'estudiants interessats en cursar carreres científiques i tècniques, en particular als països més desenvolupats (OCDE, 2006; Sjøberg i Schreiner, 2010).

Davant la necessitat de garantir una alfabetització científica de tots els ciutadans i de promoure vocacions per carreres científiques i tècniques entre els joves, sorgeix la necessitat d'innovar en l'actual manera d'ensenyar i aprendre ciències. Algunes de les iniciatives que solen engegar-se des del camp de la didàctica de les ciències són:

- Fer recerca per aclarir les necessitats i les dificultats dels estudiants i/o dels professors entorn a una temàtica o a una competència específica.
- Desenvolupar materials, propostes i enfocaments didàctics innovadors per a l'ensenyament de les ciències inspirats o basats en resultats de recerca (*disseny basat en la recerca*).
- Fer recerca entorn de les innovacions dissenyades en base a resultats de recerca (*recerca basada en el disseny*, *recerca sobre el desenvolupament*) per tal de millorar la pròpia innovació i, a més, refinar la pràctica del disseny i desenvolupament.
- Repensar la formació de professors i, en definitiva, la relació entre recerca educativa i pràctica docent, per tal de promoure un major impacte en la pràctica docent i en la política educativa.

Aquest treball de tesi aborda i detalla les tres primeres iniciatives, ja que totes elles s'han dut a terme al llarg d'aquest treball de recerca sobre el procés de desenvolupament iteratiu d'una innovació. D'aquesta manera, la recerca que es presenta s'emmarca dins del paradigma de la recerca basada en el disseny d'una innovació, tot explicitant com va ser el propi procés de disseny basat en resultats de recerca.

En general, podem dir que les motivacions d'aquesta recerca sobre el desenvolupament són diverses. D'una banda, perseguim la utilitat i l'eficàcia de la innovació dissenyada en contextos determinats i dels resultats d'aquesta recerca per a la pràctica educativa. D'altra banda, també estem tractant de contribuir a desenvolupar els marc teòrics i metodològics existents sobre el procés de desenvolupament d'innovacions, per tal que puguin ser d'utilitat per a la comunitat de recerca en didàctica de les ciències.

No són gaire comuns els estudis empírics que donen compte de detalls rellevants del procés de refinament d'innovacions, tot analitzant els diversos canvis que aquest procés de desenvolupament comporta i que, al mateix temps, suggereixin maneres de superar els punts febles de la innovació dissenyada o les dificultats identificades. En paraules de Lijnse (2010, p. 81), "tot i que el desenvolupament curricular és una activitat creativa, aquesta creativitat hauria de fonamentar-se en coneixement i experiència didàctica ja que requereix el domini de la matèria a ensenyar, alhora que requereix una visió adequada d'un 'bon ensenyament', de manera que el coneixement didàctic i les habilitats creatives es puguin posar en pràctica amb suficient qualitat". Així, el desenvolupament curricular es presenta com una activitat força complexa per la qual caldria disposar de teories didàctiques empíricament refinades que puguin guiar aquest desenvolupament. La nostra perspectiva és que fan falta recerques profundes que proporcionin orientacions plausibles sobre com refinar una innovació educativa de manera que aquest procés no es dugui a terme per intuïció sinó en base a resultats de recerca.

De fet, quan es parla de refinament existeix l'aspiració subjacent de millora de la pràctica. Però, tal com indica Millar (2010), no hi ha mesures de qualitat públicament consensuades que permetin reconèixer la millora d'un resultat d'aprenentatge o d'un procés. En aquest sentit, un ha de començar per decidir com podrà identificar els resultats d'aprenentatge que desitja. I, en el millor dels casos podrà fer recomanacions sobre com ensenyar un determinat contingut a un cert tipus d'alumnes, en contextos específics, de manera que permeti optimitzar (però de cap manera garantir) els resultats d'aprenentatge esperats.

1.2. Per què ens interessem per les seqüències d'ensenyament i aprenentatge?

After all the collecting of "butterflies" in those years of alternative conceptions, here was someone saying, Now we'll try to make use of them.

Gerard Thijs (en referència als estudis de John Clement)

Fensham (2004, p. 59)

Durant les passades dècades, es van dur a terme múltiples estudis empírics sobre concepcions dels estudiants entorn de diversos conceptes i fenòmens científics, i notables desenvolupaments teòrics sobre l'aprenentatge com activitat constructiva. No obstant, malgrat aquestes contribucions, les metodologies d'ensenyament segueixen sent molt resistents al canvi i la innovació en els currículums de ciències és molt lenta en la majoria de països. Com explica Constantinou (2010), a la majoria de sistemes educatius els professors fonamenten les seves classes en els llibres de text, en els manuals de laboratori i en els exercicis pràctics. Però sovint, aquests materials actuen com una barrera més que com un facilitador d'un ensenyament de qualitat ja que promouen la memorització més que el pensament crític, i/o ignoren importants resultats de la recerca a l'hora de ser dissenyats.

Paral·lelament, des del camp de la didàctica de les ciències s'han anat desenvolupant diversos tipus d'activitats educatives i noves propostes inspirades en la recerca per tal de millorar la comprensió dels estudiants entorn del coneixement científic. En conseqüència, una important línia de recerca des de fa alguns anys ha estat el disseny, implementació i avaluació de seqüències orientades a una temàtica concreta per a l'ensenyament de les ciències.

El terme *seqüència d'ensenyament i aprenentatge* (SEA a partir d'ara)[1] va ser introduït després d'un simposi internacional sobre disseny i validació de SEAs des d'una perspectiva de recerca, que va tenir lloc a París a l'any 2000. L'edició especial de la revista International Journal of Science Education de l'any 2004 va recollir una bona part de les contribucions dels autors que van assistir a aquell simposi. Actualment aquest terme s'utilitza àmpliament per denotar una seqüència d'activitats d'ensenyament i aprenentatge sobre un contingut determinat inspirada en resultats de recerca. En paraules de Méheut i Psillos (2004, p. 516), "una SEA és alhora una activitat de recerca intervencionista i un producte, que inclou activitats d'ensenyament i aprenentatge fonamentades en la recerca i empíricament adaptades al raonament dels alumnes. Sovint també s'inclouen les guies pel professorat". Ametller *et al.* (2005) afirmen, a més, que la transformació de resultats de recerca en exemples pràctics útils a l'aula, com les SEAs, és un mètode d'èxit per disseminar tals resultats entre els professors.

Una característica distintiva d'aquest tipus d'activitats i productes és el seu caràcter dual, que involucra recerca i desenvolupament amb l'objectiu de vincular estretament l'ensenyament proposat i l'aprenentatge esperat d'un contingut determinat per part de l'alumnat. En l'àmbit europeu de la recerca en didàctica de les ciències, la primera persona que va destacar la importància de la recerca sobre SEAs va ser Lijnse (1995), que va descriure aquest tipus d'activitat com un tipus de recerca sobre el desenvolupament.

Molts treballs publicats presenten i discuteixen els resultats d'aprenentatge dels alumnes a partir de diverses SEAs. Malgrat el detall amb que aquests treballs descriuen els resultats d'aprenentatge, sovint no expliciten i aclareixen les decisions i les hipòtesis a l'hora de dissenyar la SEA ni l'enfocament didàctic de la mateixa. Tampoc es sol detallar com ni amb quins criteris aquestes SEAs són refinades o redissenyades al llarg del temps fins a validar-les. Això podria ser degut a la limitada extensió dels articles de revista en els quals solen publicar

[1] Traducció de l'anglès del terme *teaching-learning sequence* (TLS).

els seus treballs els dissenyadors de SEAs, o també a la gran quantitat de coneixement tàcit involucrat en l'ensenyament d'un contingut específic, o també pot ser degut a la manca d'eines per representar els processos d'ensenyament, disseny o refinament.

En aquest sentit, en els últims anys diversos autors s'han esforçat per elaborar sòlids marcs teòrics i eines metodològiques per guiar el disseny i validació de seqüències d'ensenyament i aprenentatge. Alguns dels exemples més rellevants són:

- L'*enginyeria didàctica* (Artigue, 1988)
- El *model de reconstrucció educativa* (Duit, Gropengieβer i Kattman, 2005).
- La noció de *requeriment d'aprenentatge*[2] (Leach i Scott, 2002) i *d'informe de disseny*[3] (Leach, Ametller i Scott, 2010).
- Les *estructures didàctiques* (Lijnse i Klaassen, 2004).
- La *teoria dels dos móns* (Buty, Tiberghien i Le Maréchal, 2004).

El principal objectiu de tots aquests enfocaments és el de "reduir la incertesa en la presa de decisions en dissenyar i avaluar intervencions educatives" (van den Akker, 1999, p. 5).

No obstant, tal com mencionàvem en l'apartat anterior, no s'ha destinat la mateixa quantitat d'esforços a fer explícites les característiques dels processos d'avaluació i refinament de SEAs. És per aquest motiu que aquest treball de tesi s'adreça a analitzar el procés de desenvolupament iteratiu - entès com un procés cíclic de disseny, implementació, avaluació i refinament – d'una SEA que tracta un contingut específic com el de les propietats acústiques dels materials. Podríem encara preguntar-nos per què voldríem teoritzar el desenvolupament de SEAs? Ens sembla convincent donar la mateixa resposta d'Ogborn (2010, p.

[2] Traducció de l'anglès del terme *learning demand.*
[3] Traducció de l'anglès del terme *design brief.*

69), que considera que la teoria resultant faria el procés una mica "més científic i tècnic i, d'aquesta manera, una mica menys propens al fracàs".

1.3. Per què abordem el tema de les Propietats Acústiques dels Materials?

La Didáctica de las Ciencias debería fundamentar con valentía nuevas propuestas de temas para la ciencia escolar adecuadas a las diversas audiencias, que ya no son los antiguos candidatos a las disciplinas universitarias de siempre.
Izquierdo-Aymerich (2005, p. 120)

Clearly research can only claim to say something about 'how to teach X', not about 'whether to teach X'
Millar (2010, p. 57)

Estem d'acord amb Izquierdo-Aymerich (2005), en que un dels problemes propis de la didàctica de les ciències és com seleccionar adequadament què ensenyar, per tal que els alumnes puguin aprendre-ho. Acceptar que això és un problema significa també que els continguts a ser ensenyats no estan prefixats i poden canviar-se en funció dels objectius d'aprenentatge que s'hagin establert. A més, tal com afirma Millar (2010), les decisions sobre què ensenyar, quin enfocament escollir per un tema determinat, en quins aspectes posar èmfasi, amb quina profunditat tractar-los, etc., estan carregades de valors. Aquestes decisions estan influenciades per les nostres visions sobre per què ensenyem ciències a un particular grup d'alumnes, què significa ensenyar i aprendre ciències, i per què cal promoure certs resultats d'aprenentatge.

Tal com suggereixen diversos autors, el coneixement a ensenyar amb una finalitat educativa determinada ha d'establir-se a través d'un complex procés de "transposició didàctica" (Chevallard, 1991) o de "reconstrucció educativa" (Duit et al., 2005). Segons el model de reconstrucció educativa, la selecció de continguts a ensenyar hauria de tenir en compte les necessitats (o requeriments) d'aprenentatge dels alumnes i hauria de reconsiderar el contingut científic a ser ensenyat des d'una perspectiva educativa. És per aquest motiu que caldria considerar tant el contingut científic a ensenyar des de diferents perspectives (disciplinar, històrica, epistemològica), com els resultats de recerca sobre l'ensenyament d'aquest contingut i sobre les dificultats d'aprenentatge dels alumnes entorn a aquest contingut.

La reflexió sobre els continguts a ensenyar prové, d'una banda, del gran canvi que ha suposat plantejar la necessitat d'un ensenyament de la ciència per a tothom que persegueixi l'objectiu de l'*alfabetització científica* i, més recentment, la competència científica de la ciutadania. En aquest context de repensar els continguts a ensenyar es redefineixen els moviments CTS (Ciència, Tecnologia i Societat), apareixen noves assignatures de ciències, com les Ciències per al Món Contemporani, i s'introdueixen las controvèrsies sociocientífiques en els currículums de ciències. En conseqüència, els currículums oficials de ciències han anat canviant al llarg dels anys.

En el nostre context, el currículum oficial de ciències només dóna algunes orientacions generals sobre què ensenyar però la concreció dels continguts a ensenyar a l'aula recau fonamentalment sobre l'escola i el professorat. És dins d'aquest context que un grup de professors de secundària i investigadors de la universitat vam emprendre la tasca de desenvolupament d'una SEA que tractés el tema de les propietats acústiques dels materials. La selecció d'aquest tema va tenir en compte diverses motivacions:

- D'una banda, volíem abordar el tema de la ciència de materials per tal d'apropar aquesta àrea de recerca científica a l'alumnat. Si bé en l'actualitat la ciència de materials és considerada un dels camps interdisciplinars més actius, que utilitza coneixement de diverses disciplines científiques i tècniques per desenvolupar aplicacions destinades a un ampli rang de necessitats socials i tecnològiques, aquest encara roman bastant absent en els currículums de ciències de secundària. Considerem, doncs, que apropar la ciència de materials a l'escola pot permetre que els alumnes desenvolupin un cert coneixement epistemològic sobre la relació entre ciència, tecnologia i societat.

- En particular, vam considerar rellevant pels alumnes el tema de la contaminació acústica ja que és considerada una amenaça ambiental que no només és molesta sinó que pot causar problemes de salut. Considerem que la comprensió i la conscienciació d'aquest problema passa per la comprensió de com es propaga i com s'atenua el so. En aquest sentit, el nostre propòsit consisteix en promoure la comprensió i presa de consciència del problema de contaminació acústica, tot desenvolupant el coneixement dels alumnes sobre l'Acústica.
- D'altra banda, vam escollir el tema de les propietats dels materials per tal de fer conscients als alumnes de les relacions entre certes propietats dels materials, el seu comportament acústic i la seva estructura interna. D'aquesta manera era el nostre propòsit fer als alumnes capaços d'escollir materials adequats segons unes solucions requerides.
- Finalment, considerem que aquests continguts són pertinents per alumnat de quart d'ESO, ja que el currículum oficial de ciències a Catalunya per aquest nivell inclou l'estudi de les ones sonores i de l'estructura i propietats de la matèria, com a continguts a tractar al llarg del curs. Així doncs, la nostra selecció integra continguts com el so i les propietats i estructura interna dels materials, que tradicionalment s'estudien separadament des de l'assignatura de física i química. Alhora, hem tingut en compte el tema de la contaminació acústica i les mesures d'aïllament i condicionament acústic, com a context rellevant per contribuir a l'alfabetització científica dels alumnes de 15-16 anys.

Capítol 2

Objectius de la recerca

Amb la intenció de contribuir als buits de coneixement anteriorment mencionats, aquest treball de tesi va dirigit a descriure, analitzar i interpretar el procés de desenvolupament iteratiu d'una seqüència d'ensenyament i aprenentatge sobre propietats acústiques dels materials, des del seu disseny original, analitzant les diverses etapes d'implementació, avaluació i refinament fins a la validació de la mateixa. Aquest estudi dedica especial atenció a l'experimentació amb la seqüència didàctica dissenyada amb un doble objectiu:

Objectiu 1. Caracteritzar el procés de disseny i de refinament d'una SEA sobre Propietats Acústiques dels Materials, tot avaluant la seva qualitat segons els criteris (validesa, utilitat/viabilitat i eficàcia) proposats per van den Akker (1999).

Objectiu 2. Descriure la dinàmica de desenvolupament de models conceptuals d'atenuació del so i del comportament acústic dels materials per part dels alumnes al llarg de la implementació de la SEA dissenyada, i avaluar la influència de determinades activitats de la SEA en l'aprenentatge dels alumnes.

En particular, aquest treball de tesi tracta de respondre les següents preguntes de recerca:

Preguntes de recerca relatives a l'Objectiu 1:

1. Quins aspectes problemàtics relatius a la SEA dissenyada s'han identificat en analitzar-la i avaluar-la (a cada cicle) després d'haver-la implementat a classe amb estudiants de 4art d'ESO?
2. Quins canvis s'introdueixen a la SEA per superar els aspectes problemàtics identificats?
3. Quines són les "forces impulsores del canvi" o "motius crítics" pels canvis introduïts a la SEA dissenyada?

Preguntes de recerca relatives a l'Objectiu 2:

4. Com progressen els alumnes des dels seus models mentals preliminars - d'atenuació del so en materials i del comportament acústic dels materials - cap als models conceptuals esperats al llarg de la implementació de la SEA dissenyada?
5. Quines activitats de la SEA dissenyada tenen un major impacte en el desenvolupament dels models conceptuals per part dels alumnes?

Capítol 3

Justificació de la unitat temàtica

Aquest treball de tesi és un compendi de quatre publicacions. Cadascun d'aquests articles o capítols, malgrat ser escrits de manera independent per ser publicats a diferents revistes o llibres, han estat el resultat de la recerca portada a terme al llarg del projecte europeu *Materials Science* i tenen un marc teòric i metodològic comú, com és el de la recerca basada en el disseny. Això justifica la unitat temàtica d'aquest compendi.

A continuació, desenvoluparem amb més profunditat la visió comuna a les publicacions que formen el compendi d'aquesta tesi. D'aquesta manera, pretenem mostrar la nostra perspectiva respecte a la recerca basada en el disseny de SEAs.

3.1. El context de la recerca: el projecte *Materials Science*

El projecte *Materials Science* va ser finançat pel 6è Programa Marc de la Unió Europea, sota l'àrea de "Ciència i Societat", al llarg de tres anys (2007-2009). El nom complet d'aquest projecte, coordinat pel professor Constantinos P. Constantinou, és *"University-school partnership for the design and implementation of research-based ICT-enhanced modules on Material Science"*.

El focus del projecte va ser el desenvolupament de materials d'ensenyament innovadors sobre ciència de materials per alumnat d'entre 10 i 17 anys, que s'adherissin a les teories i enfocaments sobre ensenyament i aprenentatge de les ciències contemporanis i posessin èmfasi en vincular resultats de recerca i pràctica educativa. Específicament, els materials d'ensenyament es basen en el disseny basat en la recerca, en el refinament iteratiu i en el disseny participatiu.

Durant el projecte, sis SEAs (corresponents als sis grups participants en el projecte) van ser desenvolupades i implementades per cadascun dels grups, avaluades i redissenyades al menys dues vegades en el sistema educatiu local. Aquest procés de refinament iteratiu va permetre proporcionar una comprensió més profunda sobre el disseny, avaluació i validació de SEAs.

A nivell nacional, la col·laboració universitat-escola a la que fa referència el títol del projecte es va concretar en la formació d'un grup de vuit professors de ciències de secundària de quatre centres escolars diferents, i de tres investigadors en didàctica de les ciències de la Universitat Autònoma de Barcelona. Aquest grup de treball local es va establir com una *comunitat de pràctica* (Wenger, 1998), on l'experiència i el coneixement de totes les parts van tenir-se en compte a l'hora de dissenyar i refinar la SEA sobre propietats acústiques dels materials (Pintó *et al.*, 2009). Aquesta dinàmica de treball va venir suggerida per rellevants recerques (Pintó, 2005; Viennot, Chauvet, Colin i

Rebmann, 2005) que han mostrat que un paper passiu per part del professorat quan dissenya una innovació pot tenir profundes implicacions en la seva implementació, sovint distorsionant detalls crítics de la fonamentació de la mateixa. Com diuen Andersson i Bach (2005, p. 197), "els canvis a la pràctica docent basats en la recerca no poden ser forçats des de dalt; només poden aconseguir-se mitjançant la col·laboració d'investigadors i professors en actiu, com a col·legues durant el procés".

Els mateixos professors que formaren part del grup de treball local també van implementar les consecutives versions (versió original, segona versió resultant del primer procés de refinament i tercera versió resultant del segon procés de refinament) de la SEA dissenyada a les seves classes de ciències de 4t d'ESO al llarg de tres cursos consecutius (2007/08, 2008/09, 2009/10).

La Figura 1 mostra un diagrama del procés de desenvolupament iteratiu de la SEA sobre propietats acústiques dels materials, portat a terme pel nostre grup de treball local.

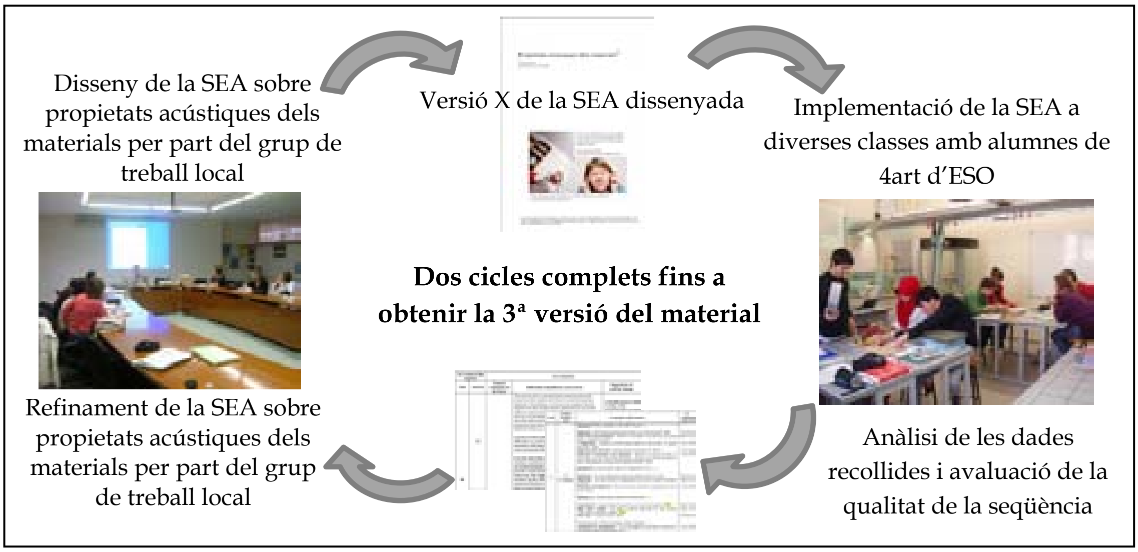

Figura 1. Etapes del procés de desenvolupament iteratiu de la SEA sobre propietats acústiques dels materials.

3.2. El paradigma de la recerca basada en el disseny (DBR)

To guide the design of curriculum, we need answers to questions that can be answered only through empirical investigation. Intuition, experience, and specific theories can all provide guidance but not reliable predictions
Heron (2003, a, p. 344).

If one attempts to interpret what is going on in science classrooms directly in terms of general (learning) theories, one immediately faces the problem that, on application, such theories only result at best in heuristic rules. Such rules simply cannot guarantee that the teaching process that is supposed to be governed by them will have the necessary didactical quality.
Lijnse i Klaassen (2004, p. 538)

3.2.1. Trets característics del paradigma de la recerca basada en el disseny

Aquest treball de tesi s'inscriu dins del paradigma de la *recerca basada en el disseny*[4] (DBR a partir d'ara). La DBR ofereix una nova visió de la teoria sobre el disseny, desenvolupament i refinament, tot contribuint a l'elaboració d'una ciència del disseny en educació (Akilli, 2008). El col·lectiu de la recerca basada en el disseny (DBRC, 2003, p.5) caracteritza la DBR com un paradigma de recerca que "combina recerca educativa empírica i disseny d'entorns d'aprenentatge basat en teories".

Diversos investigadors que han portat a terme recerques basades en aquest paradigma de recerca i han contribuït a definir-lo (diSessa, 2006; DBRC, 2003) destaquen els següents trets principals comuns a aquests tipus de recerques:

[4] Traducció de l'anglès del terme *design-based research* (DBR).

- Són intervencionistes, és a dir, exploren el món (educatiu) actuant sobre ell, partint del disseny d'una innovació, ja sigui una pràctica, un objectiu, un material, una SEA o una comunitat. En aquest sentit, aquestes recerques són pragmàtiques, ja que la finalitat del disseny i implementació d'intervencions educatives és la de solucionar problemes de la pràctica educativa.
- Són iteratives, és a dir, tant el desenvolupament de la innovació com la recerca sobre la mateixa tenen lloc al llarg de cicles continus de disseny, implementació, anàlisi, avaluació, refinament i redisseny, enriquits amb resultats de recerca, amb l'objectiu d'assolir un equilibri adient entre objectius esperats i resultats obtinguts.
- Són interactives, ja que impliquen la col·laboració d'investigadors, dissenyadors i professors per tal de garantir que la innovació dissenyada assoleixi uns determinats objectius a la pràctica. De fet, la DBR es va concebre com una resposta a les crítiques sobre la separació entre recerca i pràctica educativa. No obstant, considerem que la DBR difereix d'altres paradigmes com el de la recerca acció quant a la implicació de tots els participants en totes les fases de desenvolupament, ja que a la DBR els professors sovint no estan involucrats en la planificació de la recerca ni en l'anàlisi de dades recollides durant la seva pròpia pràctica, tot i que participin en el disseny de la innovació i valoració de la seva implementació.
- Són generadores de teories "humils" (diSessa, 2006), que donin compte dels principis teòrics de disseny i refinament de la innovació. D'aquesta manera, aquestes recerques no es centren només en documentar l'èxit o el fracàs d'una innovació sinó també en analitzar certs elements de la intervenció que ajudin a refinar la comprensió sobre com "funciona" la innovació en escenaris autèntics, sobre com aprenen els alumnes al llarg de la intervenció. Aquests principis teòrics, també anomenats *prototeories* (DBRC, 2003), *teories provisionals sobre (l'ensenyament de) un contingut específic* (Andersson i Bach, 2005), *teories humils* (diSessa, 2006), *teories*

locals (van den Akker, Gravemeijer, McKenney i Nieveen, 2006), *teories específiques* (Tiberghien, Vince i Gaidioz, 2009) o *principis de disseny* (Kali, 2009; Millar, 2010), consisteixen en totes aquelles decisions o pautes, fonamentades en premisses teòriques i en resultats empírics, que orienten el disseny d'una intervenció o d'un material per a l'ensenyament i aprenentatge d'un contingut concret.

El col·lectiu d'investigadors que porten a terme recerques basades en el disseny considera que la necessitat d'aquest tipus de recerques sorgeix de la constatació de que les grans teories educatives (com el constructivisme, el socioconstructivisme, la teoria de la cognició situada, etc) són massa generals i poc eficaces a l'hora de recolzar la presa de decisions relacionades amb el disseny d'innovacions i amb l'ajustament/refinament d'intervencions que "no acaben de funcionar" (diSessa, 2006).

Per aquesta raó, un dels objectius d'aquest treball de tesi, tal i com s'ha indicat al capítol 2, és també explicitar els principis de disseny de la SEA sobre propietats acústiques dels materials i, posteriorment, refinar-los en funció dels resultats d'aprenentatge dels alumnes en participar en la implementació de la SEA dissenyada.

Tal com diu Heron (2003, b, p. 355), moltes de les decisions que prenem a l'hora de dissenyar materials reflecteixen dos tipus de principis:

- Principis generals sobre com aprenen els alumnes i sobre la naturalesa del coneixement científic.
- Principis específics sobre com aprenen els alumnes el contingut específic sota consideració.

La Taula 1 resumeix els principis de disseny generals i específics en base als quals ha estat dissenyada i refinada la SEA sobre propietats acústiques dels materials. Aquests principis de disseny han estat descrits amb detall a les diferents publicacions que formen part del compendi d'aquest treball de tesi.

Taula 1. Principis de disseny generals i específics de la SEA sobre propietats acústiques dels materials

Principis de disseny generals	**Principis de disseny específics**
• Aprenentatge basat en la participació activa dels alumnes i en la col·laboració entre iguals i amb el professor/a. • Ensenyament orientat per l'enfocament de la *indagació centrada en la modelització* (Schwarz i Gwekwerere, 2007; Khan, 2007; Löhner, van Joolingen, Savelsbergh i van Hout-Wolters, 2005; Stewart, Cartier i Passmore, 2005; Windschitl, Thompson i Braaten, 2008), segons el qual es promou que l'alumnat desenvolupi *models conceptuals* (Greca i Moreira, 2000) a mesura que tracta de respondre interrogats plantejats mitjançant la recollida i/o el tractament de dades. • *Contextualització i problematització* del contingut a aprendre (Lijnse, 2005), per promoure en els alumnes una significativitat d'allò que s'ensenya. • *Èmfasi en la metacognició* (Gunstone, 1992), per tal que els alumnes siguin conscients dels propòsits de les activitats i sentin la necessitat d'ampliar el seu coneixement conceptual i les seves experiències.	• La selecció i seqüenciació del contingut a ensenyar de la SEA sobre propietats acústiques dels material es basa tant en l'anàlisi crític del contingut com en els resultats de recerques sobre comprensió conceptual dels alumnes (veure Publicació 1 i 2 del compendi de la tesi) sobre la naturalesa i la propagació del so (Eshach i Schwartz, 2006; Hrepic, Zollman i Rebello, 2010; Linder, 1992, 1993; Maurines, 1993; Mazens i Lautrey, 2003; Wittmann, Steinberg i Redish, 2003), l'atenuació del so i les propietats acústiques dels materials (Hernández, Couso i Pintó, 2011, a).

En resum, el present treball de tesi pot ser caracteritzat pels mateixos trets comuns a qualsevol recerca basada en el disseny ja que: (i) explora unes intervencions educatives determinades en uns contextos concrets en els quals s'intervé a partir del disseny, implementació i refinament d'una SEA sobre propietats acústiques dels materials; (ii) és iterativa ja que la recerca es porta a terme al llarg de diverses fases de disseny, implementació, avaluació i refinament de la SEA en diversos cursos acadèmics; (iii) és interactiva ja que implica la col·laboració d'investigadors i professors al llarg del desenvolupament de la SEA; i (iv) contribueix al desenvolupament dels principis teòrics en els quals hem basat el disseny de la SEA.

3.2.2. Aspectes metodològics del paradigma de la recerca basada en el disseny

Tal com afirma Akilli (2008), la DBR és més un paradigma de recerca que no pas una metodologia de recerca. De fet, autors com Kelly (2004) argumenten que part de la metodologia d'una recerca basada en el disseny consisteix en aclarir en quina etapa i amb quins propòsits són apropiats (o no) uns determinats mètodes.

Segons això, aquest treball de tesi ha utilitzat diverses metodologies a l'hora de dur a terme les recerques adreçades als diferents objectius, mencionats al capítol 2.

Un dels objectius de la nostra recerca és millorar la qualitat de la SEA dissenyada per tal d'analitzar per què aquesta funciona o no a la pràctica i quines són les maneres de superar les dificultats identificades. Per aquest motiu, vam recollir informació dels aspectes problemàtics de la SEA, dels tipus de canvis que vam considerar necessaris de realitzar en el disseny original i dels resultats de consecutives implementacions de la SEA refinada. Això ens va permetre caracteritzar el procés de refinament de la SEA sobre propietats acústiques dels materials (veure Publicació 3 del compendi de la tesi).

Ara bé, com diuen Collins, Joseph i Bielaczyc (2004, p. 35), "hi ha molts aspectes diferents que fan que un disseny sigui efectiu i, per això, tant els dissenyadors com els avaluadors necessitarien 'posar-se diferents barrets' a l'hora de dissenyar i avaluar intervencions educatives". Kelly (2004) ressalta la necessitat de definir uns criteris d'avaluació dels productes dissenyats, uns objectius prou explícits que permetin concretar allò que hauria d'assolir-se durant la implementació i allò que hauria de modificar-se en cas que no s'hagi assolit allò que s'esperava. Al llarg de la recerca sobre el procés de desenvolupament iteratiu de la SEA que vam dur a terme, l'avaluació de la qualitat de la SEA dissenyada va seguir els següents criteris proposats per van den Akker (1999):

- La *validesa*, que fa referència al grau de fonamentació teòrica de la SEA dissenyada i a la consistència entre les diferents parts de la SEA. La validesa pot ser avaluada per experts externs.
- La *utilitat* o *viabilitat*, que fa referència al grau d'interès i utilitat en condicions "normals" que els usuaris (i altres experts) perceben de la SEA.
- L'*eficàcia*, que fa referència al grau de consistència entre les experiències i resultats de la implementació de la SEA i els objectius esperats.

Quant a l'avaluació de l'eficàcia d'una SEA en relació als objectius esperats, Méheut i Psillos (2004) distingeixen entre diferents enfocaments metodològics:

- *Procediments pre-test i post-test*

És la metodologia més freqüentment adoptada per avaluar l'eficàcia d'una SEA en relació a uns objectius d'aprenentatge específics. Les dades poden ser recollides mitjançant proves administrades al final de la seqüència. Aquests resultats finals poden ser comparats amb els obtinguts pels mateixos alumnes abans de la implementació de la SEA (avaluació "interna") o amb els obtinguts per un altre grup d'alumnes del mateix nivell que no han participat en la implementació de la mateixa seqüència (avaluació "externa"). El propòsit de l'avaluació interna és el de comprovar l'eficàcia de la seqüència en relació als objectius inicials. En canvi, l'avaluació externa pretén determinar si la seqüència didàctica dissenyada és més eficaç per a l'aprenentatge dels alumnes que altres tipus d'ensenyament que es tenen com a referència.

- *Estudi de l'evolució de l'aprenentatge dels alumnes*

Altre tipus d'enfocament cada vegada més comú en el camp de la recerca en l'educació científica (Duschl, Maeng i Sezen, 2011; Niedderer i Goldberg, 1995; Schwarz et al., 2009; Scott, 1991; Talanquer, 2009; Viennot i Rainson, 1999) consisteix en analitzar el procés d'aprenentatge dels alumnes. Aquest tipus d'estudi sembla indispensable si es pretén avaluar la idoneïtat dels principis de disseny d'una SEA. En definitiva, aquesta metodologia contribueix a analitzar dades diverses per tal de discutir i millorar l'eficàcia de les estratègies d'ensenyament i aprenentatge. Per aquest motiu, vam decidir analitzar les progressions d'aprenentatge dels alumnes al llarg de la SEA dissenyada amb el propòsit d'avaluar la influència de determinades activitats de la mateixa.

Segons Leach i Scott (2002), aquests enfocaments metodològics són vàlids si considerem que l'objectiu principal d'una SEA és promoure l'aprenentatge dels estudiants. No obstant, aquests mètodes no ens permeten respondre preguntes com ara: "Quins principis de disseny de la SEA i de l'entorn d'aprenentatge han estat decisius per promoure l'eficàcia del procés d'aprenentatge?". Si els investigadors només disposen de dades sobre l'aprenentatge dels estudiants i de la SEA utilitzada, però no disposen d'informació de la seva implementació, la transferència de la SEA a altres professors pot veure's limitada. Si diferents professors implementen la mateixa SEA amb grups d'alumnes similars, és molt probable que aconsegueixin diferents resultats quant a l'aprenentatge dels seus estudiants, si no tracten de portar a la pràctica les activitats de manera semblant. Per això, l'avaluació de la qualitat de la SEA sobre propietats acústiques dels materials va tenir en compte tant els resultats d'aprenentatge dels estudiants al llarg i al final de la implementació com les característiques de les activitats que els professors i els alumnes van dur a terme durant la implementació de la SEA a classe.

SECCIÓ II. PUBLICACIONS DEL COMPENDI

Capítol 4

Publicació 1

The Analysis of Students' Conceptions as a Support for Designing a Teaching / Learning Sequence on the Acoustic Properties of Materials

La publicació 1 d'aquest compendi presenta una recerca entorn a les concepcions de 72 alumnes de 4rt d'ESO i 2n de Batxillerat sobre el fenomen de l'atenuació del so i sobre les propietats acústiques dels materials. Aquest estudi parteix del principi de que qualsevol resultat de la recerca sobre com entenen els alumnes un determinat concepte o fenomen no hauria de ser "el final de la història" sinó el punt de partida per planificar sessions de classe i dissenyar materials d'ensenyament i aprenentatge.

En aquest sentit, l'article publicat a la revista *Journal of Science Education and Technology* explica com vam utilitzar els resultats d'aquesta recerca a l'hora de dissenyar una seqüència d'ensenyament i aprenentatge sobre propietats acústiques dels materials. Tot i que aquest estudi es va portar a terme en un escenari particular, diferent del context al qual es portaria a terme el disseny i implementació de la SEA sobre propietats acústiques dels materials, ha estat útil per identificar les dificultats de comprensió més comunes dels alumnes de secundària i ha proporcionat orientacions per promoure el desenvolupament de models conceptuals sobre l'atenuació del so i sobre el comportament acústic dels materials.

A continuació, es presenta l'article en el seu format de publicació i, en ell, es dóna compte dels detalls de la recerca i de les seves implicacions pel disseny basat en resultats de recerca de la SEA sobre propietats acústiques dels materials.

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The Analysis of Students' Conceptions as a Support for Designing a Teaching/Learning Sequence on the Acoustic Properties of Materials

María Isabel Hernández · Digna Couso · Roser Pintó

Abstract We believe that finding out how students think about certain topics that are covered in science classes should not be ''the end of the story'' but the starting point for planning lessons and designing materials. From this perspective, the research study presented here is intended to explore secondary school (15–18 year old) students' preconceptions of sound attenuation, and of the properties and internal structure of materials. Specifically, we analysed students' explanations for the fact that some materials attenuate sound more than others. This study was conducted within a particular scenario, in which 72 students participated in laboratory sessions aimed at developing students' understanding of the nature, propagation and attenuation of sound. From the analysis of students' explanations, we could identify some conceptions of sound attenuation in materials (e.g. as a result of hindering the entrance of sound, or as a result of capturing sound). The results of this study also indicate that the role of properties of a material and the role of the internal structure that students associate with its acoustic behaviour depend on their conceptions of sound attenuation. We used these results as support for the design of a research-based teaching/learning sequence on the Acoustic Properties of Materials, which is intended to facilitate students' overcoming the specific conceptual difficulties identified in this research study and promote students' development of conceptual models of sound attenuation.

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Introduction

It has been widely evidenced that students develop ideas about natural phenomena before they are taught science in school. It is also widely agreed that such ideas should not be seen as simply pieces of misinformation, but as students' ways of constructing events and phenomena which can be coherent and fit with their domains of experience, even though they may differ substantially from the scientific view. We agree with Driver et al. (1994) that finding out how students think about the various topics covered in science classes is not ''the end of the story'' (p. 10). Science teachers have the responsibility for providing activities which enable students to make the journey from their current understanding of the world to the accepted scientific view.

There is a wide consensus in science education that effective science teaching takes account of students' previous ideas, among other aspects. According to this view, this article presents a research study about students' preconceptions of a specific topic - sound attenuation in materials and the acoustic properties of materials - in order to provide new insights into how to teach this topic in secondary school.

Even though several research studies have analysed students' conceptions of the nature of sound, sound propagation and other sound-related phenomena such as resonance or superposition, we could not find previous published studies specifically devoted to the analysis of students' conceptions of sound attenuation in materials and the acoustic properties of materials. That was one of the main reasons to conduct this study.

Another reason for conducting this research relates to the particular context in which we planned to carry out the study. According to the available research data which supports that students' thinking is deeply situated in specific contexts (Taber 2000), we assumed that the students' responses that might be obtained in the particular scenario we used (understood as the setting and the activities) would presumably be different (and even richer and more varied) from students' responses to the same questions had they been asked before having performed some previous activity related to the same phenomenon (sound attenuation). Multiple possible contexts can be used to explore children's thinking about sound attenuation, but we selected a (technologically and pedagogically) rich scenario in which students were asked about their thinking of sound attenuation referring to one experimental task that they had previously performed during a laboratory session.

In particular, the research we present here was aimed at contributing to the design of a teaching/learning sequence (TLS) on the Acoustic Properties of Materials (APM) intended for 15–16 year-old secondary school students. Thus, this article will report on some of the previous steps leading up to the design of the TLS on APM, which was carried out after the research reported here and took its findings into account.

First of all, this paper presents a review of previous studies of students' conceptions of sound reported in the literature. Then, it explains the research study we carried out on students' preconceptions of the specific topics we wanted to address in the sequence—sound attenuation and the acoustic properties of materials. Finally, the article describes the findings of this research and how they were used to support the design of the teaching sequence on APM.

Students' Conceptions of Sound Before or After Formal Instruction

As mentioned before, one of the first actions carried out when designing a TLS on APM was to consider the ideas about sound usually held by secondary school students, and the difficulties they commonly have in understanding what sound is, how it propagates and how it is attenuated. According to Wittmann et al. (2003), whilst the concepts of sound and noise are part of students' everyday experience, the fact that the perception of sound is auditory and not visual makes knowing what sound is, how it propagates and how it is attenuated become even more difficult for many students.

From a scientific point of view, sound is conceived as the event produced by the vibrations of an object called the sound source. These vibrations are propagated through an elastic medium which gradually transmits its state of compression or dilation, without transport of matter. The important point here is that sound, as a wave, is a process of energy transfer and therefore has the physical properties of processes, not those of objects (Lawrence 2008). Most of the research studies devoted to analysing students' conceptions of sound concluded that this key idea is not understood by most students.

Below, we summarise the main findings of several previous studies on students' common conceptions of sound, before or after formal instruction, distinguishing two categories: conceptions referring to what sound is (i.e. ontology attributes) and how it propagates (mechanisms and trajectory), and conceptions referring to the interaction between sound and the medium through which it propagates.

Students' Conceptions of the Nature and Propagation of Sound

Several studies suggest a naïve mental model of sound propagation, according to which sound travels as a particle-like object. This kind of mechanistic spontaneous reasoning has been evidenced in elementary school students (Mazens and Lautrey 2003), as well as in secondary school students (Eshach and Schwartz 2006; Maurines 1993) and undergraduate physics students (Hrepic et al. 2010; Linder 1992; Wittmann et al. 2003). Some of these authors generally refer to this naïve model as the ''particle model'' (Maurines 1993) or ''entity model'' (Hrepic et al. 2010) of sound propagation. These models can be characterised in terms of some of the following attributes expressed by students in the aforementioned studies:

- Sound signals are conceptualised as material objects (sound particles) created and set in motion by the source (Maurines 1993).
- Sound is considered an entity which is transported by individual molecules, which move along a medium (Linder 1992).
- Sound is considered an entity which is transferred from one molecule of a medium to another but is different from the medium where it propagates (Linder 1992).

- Sound is considered a limited substance which travels with a certain impetus, and is generally represented as an air current (Linder 1992).
- Sound is considered a substance which travels following the pattern of waves (Linder 1992).

Students' Conceptions of the Interaction of Sound with Matter

Some research studies (Linder 1993; Maurines 1993) also analysed students' explanations of the factors that affect the speed of sound, and students' ideas about the interaction of sound with a certain medium. Here we summarise the main findings that relate to our study:

- Molecules that form a medium are conceptualised as an obstacle to the propagation of sound through the medium (Linder 1993).
- The speed of sound is conceived as being dependent on the source or the signal amplitude but independent of the properties of the medium (Maurines 1993).
- Even when the speed of sound is recognised as being dependent on the density and elasticity of materials, density is often conceptualised as related only to the distance between the molecules of a medium, and elasticity is conceptualized in terms of compressibility and as inversely proportional to density (Linder 1992).
- Sound is thought to be able to propagate through the vacuum and to be transmitted through the empty spaces between the particles that form a medium (Maurines 1993).

To sum up, these research studies indicate that previous knowledge regarding sound of students at any educational level tends to be materialistic or ''based on substances''. This implies that students tend to attribute properties or the behaviours of material substances to processes or events, as in the case of sound. On the other hand, the previous studies evidence that students often attribute different roles to the medium when referring to sound propagation (facilitating or hindering sound propagation) and, moreover, the physical properties of the medium such as density and elasticity are themselves difficult to be appropriately conceptualised.

Although many aspects and attributes of the so-called ''entity model'' of sound have been described and reported by several authors, these previous research studies did not tackle the analysis of how students conceive sound attenuation or how they understand the acoustic properties of materials. For this reason, we decided to design and conduct a research study to explore 15–18 year-old students' preliminary ideas of these topics. This research study was carried out within a special scenario which is described below.

Context of the Study

The REVIR Scenario

The scenario in which this study was conducted is the REVIR project, which is an initiative of the Centre for Research in Science and Mathematics Education (CRECIM), in which secondary school students from Catalonia can access a computerised laboratory at the University (Faculty of Education). Groups of researchers and secondary school teachers collaborate to design activity sequences for labwork practice that deal with different science topics and integrate different ICT tools (simulations, computational applications and MBL technology). The aim for including these ICT tools is not only for improved learning of science content and skills, but also a greater achievement of digital competence and a more sophisticated idea of how real science is conducted in ICT-enhanced laboratories (Pintó et al. 2010).

During the REVIR sessions, classes of secondary school students (12–18 years old) spend an entire morning (4 h) working in small groups (2–4 students) with specific material prepared for the session and for the grade of the attending class. Their teachers also attend the session in order to observe their students' attitudes and skills when working with computational tools and, at the same time, they learn different ways of implementing these tools within their own lessons. Members of CRECIM implement the designed sequences and often collect data about the learning process. In short, the REVIR project is a hybrid scenario intended to contribute to both science teaching and research in science education.

The teaching sequence on Acoustics education[1] addressed to these REVIR sessions was designed and iteratively developed for several months before the data collection for the study we present here took place. This teaching sequence engages students in analysing the nature, propagation, production and hearing of sound, in monitoring and characterizing the

[1] Note that the teaching sequence on Acoustics education designed for the REVIR sessions is different from that on the Acoustic Properties of Materials (APM) which will be described later and which was designed using the results obtained from the present research study.

sounds they produce and in designing solutions to attenuate sound, the content of which is included in the official ''Physics and Chemistry'' curriculum.

The Teaching Sequence on Acoustics Education for the REVIR Scenario

As a method to involve students in the session, the teaching sequence begins by placing students in a real context with some significance to them, and by posing a meaningful problem. The aim is to give them a purpose for the tasks that they will carry out during the session, challenging them to find a solution to the following problem:

> We are a rock team practising in the attic of a building. While we were practising, the police came due to some complaints from the neighbours. We must attenuate the sound we produce by using some materials. How can we manage to do it?

The teaching sequence on Acoustics education is structured around three tasks:

(a) *Let's explore and describe sound*

Students explore a simulation,[2] which represents the propagation of sound in terms of the vibration of the particles that form a medium, and also graphically represents the displacement of particles over time. Students are asked a series of questions that are intended to guide them when exploring the simulation about sound and its characteristics. The goal of this first task is that students revise/clarify their conceptions of sound propagation in terms of the vibrations of particles and the transfer of energy but not matter. Throughout the task, students discuss the meaning of the variables that characterise sound waves (frequency, period, amplitude) to guarantee that they share a specific language with a common meaning during the session.

(b) *Let's graphically analyse different sounds and noises*

Students analyse the graphical representations of different real sounds by means of a freeware application[3] to characterise sound waves produced by different instruments in terms of their frequency and shape, related to the pitch and timbre respectively. Therefore, students relate the pitch of different sounds to the frequencies they calculate from the period expressed in the graphs, and they relate the shape of the graphs to the characteristic timbre of an instrument. Students also graphically analyze the difference between sound and noise. In short, students analyse in depth one of the variables that characterise sound: frequency (or period).

(c) *Let's measure sound intensity level*

In this final task, students focus on another key variable that characterises sound waves: the amplitude. First of all, students relate the amplitude of sound waves to the sound intensity level, magnitude that they learn to measure with a sound level meter. Next, students design and perform an experiment to compare the capacity for attenuating sound with three different materials: expanded polystyrene, glass wool and rock wool. At this point, the only operational definition of sound attenuation that is made explicit and shared among students is that sound attenuation implies a decrease in sound intensity level. Although this activity engages students in analysing the acoustic behaviour of different materials, this activity is not intended to engage students in discussing or analysing the properties of materials that influence their acoustic behaviour.[4] Once the students perform the experiment and obtain the resulting measurements, they are expected to make informed decisions on the material they would propose as soundproofing solutions for the noise control of the room of the problem posed at the start of the session.

The Experiment to Analyse Materials' Capacity for Attenuating Sound

The experimental setup used in the investigation carried out by the students in the third task of the teaching sequence contains the following elements: a *sound source*, *samples of material* and a *detector*.

Regarding the sound source, students are provided with broadband buzzers, which emit sound at a constant intensity level.

The samples or plates of material are contained inside a cardboard box covering all six sides. The cardboard box itself represents the structure of a room or closed space, which has a particular geometry. The plates of material covering the box (as shown in Fig. 1) represent

[2] http://www.ngsir.netfirms.com/englishhtm/Lwave.htm.

[3] Audacity (http://audacity.sourceforge.net).

[4] This is indeed the main focus of the teaching/learning sequence on the Acoustic Properties of Materials which was designed using the results obtained from the current research study.

Fig. 1 Cardboard boxes and their lids covered with rock wool, expanded polystyrene and glass wool, respectively

the samples of the material that could be used to soundproof a certain room. These samples have similar thickness (2.5 cm) to allow comparison of the capacity of the different materials for attenuating sound, instead of the effect due to the different thicknesses of the plates. Three boxes were used in order to cover each of them with plates made from a different material.

As a detector, students use sound level meters to measure the sound intensity level, which are the common instruments used in everyday life for noise control. Sound level meters are also used in connection with data capture systems (MBL technology) and computers (Fig. 2) in order to register and monitor in real time the evolution of the sound intensity level during the experiments.

Fig. 2 Experimental setup (sound level meter-MBL interface-computer, box and lid covered with a certain material, buzzer inside the box)

During the experiment, students use the sound level meter to measure the intensity level of the sound transmitted outside a box whose walls have been covered with plates made from a certain material (sample), having placed the sound source inside the box (Fig. 3). The measurement of the intensity level of the sound transmitted outside the box covered with the tested material represents the noise control measurement that would be taken at the neighbours' house. Comparing the measurements outside each box at a certain (fixed) distance from the source, students can compare the capacity of each material for attenuating sound, with the lowest measurement outside the box being associated with the best sound insulating material or with the one that has higher capacity for attenuating sound.

After describing in detail the intervention carried out during the REVIR sessions devoted to Acoustics education, in which the research data were collected, the specific research questions and methods are discussed.

Fig. 3 Experiment to test sound attenuation produced by the material inside the box

Research Questions

In designing our study, we were guided by two research questions: (a) *What preconceptions on the phenomenon of sound attenuation do secondary school students use when explaining the acoustic behaviour of materials?* (b) *Which properties and internal structure do secondary school students assign to materials according to their acoustic behaviour?*

Method

Setting and Participants

Seventy-two secondary school students from different Catalan schools constitute the sample of our study. These students came from different classes that participated in REVIR sessions that dealt with Acoustic education throughout two consecutive academic years (2006–2007, 2007–2008). The participating students were studying in the final years of secondary school (15–18 years old). Although all the participating students had, to some extent, previously studied the topic of sound during their formal science instruction, they had not formally discussed the topic of sound attenuation in materials and the acoustic properties of materials.

Data Sources

Our methodological choice consisted of an open-ended questionnaire administered at the end of the entire REVIR session on Acoustics education, after students performed the experiment already described, and without having discussed the mechanisms of sound attenuation or acoustic

Table 1 Types of students' explanations (at the end of the session) for the fact that some tested materials attenuate sound more than others

Explanation in terms of…	Description of each type of explanation	Students' quotes	Number of students
Acoustic behaviour of materials (ABM)	Students explain the different capacities for attenuating sound of different materials by providing a description of the acoustic behaviour of materials	*"[Some materials attenuate sound more than others] because they do not allow the passage of sound waves"*	39/72 (54%)
Physical properties of materials (PPM)	Students interpret the differences in sound attenuation produced by different materials in terms of their physical properties	*"[Some materials attenuate sound more than others] because they are less porous"*	63/72 (88%)
Internal structure of materials (ISM)	Students relate the different capacities for attenuating sound of different materials to their internal structure in terms of the particulate model of matter	*"[Some materials attenuate sound more than others] because their particles are more distant […]"*	8/72 (11%)

properties of the materials used during the session. For the purpose of this research, students were asked the following open-ended question concerning the third task of the session:

> Invent an explanation for the fact that some materials tested attenuate sound more than other materials

Data Analysis

We conducted a phenomenographic study using a qualitative research methodology within the interpretative paradigm, in order to investigate the different ways in which students experience something or think about a specific situation or phenomenon (Marton 1981). Thus, this phenomenographic study was intended to obtain a set of related categories that describe the qualitative differences between one students' conception and another.

Results and Discussion

Analysing students' answers, we could categorise students' explanations depending on whether they focused on the acoustic behaviour of different materials or on the physical properties or internal structure of materials. Table 1 summarises the different types of students' explanations that were identified.

As shown in Table 1, many students (54%) explained the differences in sound attenuation caused by different materials by providing a description of the acoustic behaviour of these materials (ABM). Thus, these students made explicit what they understand by sound attenuation.

Most of the students (88%) also explained possible differences in the acoustic behaviour of materials in terms of their physical properties (PPM). That is to say that students mentioned several properties influencing the particular acoustic behaviour of each material, perhaps not even eliciting their idea of sound attenuation.

We surprisingly found that 11% of students, without having been taught about the role of internal structure of a material, used a microscopic model (ISM) to justify their capacity for attenuating sound.

The previous percentages already provided evidence that in many cases students did not answer in terms of just one type of the aforementioned explanations but in terms of a combination of some of them. For example, the next student's quote illustrates an explanation that refers to a PPM, the ISM, and also makes explicit the ABM:

> If a material is denser, its particles are closer, and therefore it transmits sound better than a less dense material

We now proceed to analysing in depth and separately the types of explanations that students formulated when are asked about sound attenuation. The ABM-type students' explanations were analysed in order to answer the first research question, and the PPM and ISM-types students' explanations were analysed to answer the second research question. The content analysis of these students' explanations is described below.

Students' Conceptions of Sound Attenuation

In order to identify students' preconceptions of sound attenuation, we took a subsample of 39/72 students (54%), which is formed from those who have answered in terms of the

Table 2 Description of students' conceptions of sound attenuation

Student conception	Description of the conception	Students' quotes	Number of students
C1	Sound is attenuated by hindering the entrance of sound	*"Depending on the properties of materials, they allow the passage of waves more or less. The materials that best insulate sound, reflect waves more"*	11/39 (28%)
C2	Sound is attenuated while propagating within/through a material	*"The denser a material is, the less vibration it allows in its particles, and therefore it has more difficulty transmitting sound"*	15/39 (38%)
C3	Sound is attenuated by capturing/absorbing sound within the material	*"Some materials absorb the vibration […]more easily than others because they have small spaces full of air"*	7/39 (18%)
C4	Sound is attenuated by either reflecting or absorbing sound	*"Some materials have pores that absorb sound; others do not have [any pore] and reflect sound"*	6/39 (15%)

acoustic behaviour of materials (ABM). Table 2 shows such preconceptions.

As summarised in Table 2, more than one quarter of the reduced sample of students considers that sound attenuating materials behave as sound barriers that prevent the passage of sound through a material (C1). Accordingly, these students conceive that the only mechanism of sound attenuation is sound reflection. Students' conception of sound attenuation C1 seems to be based on an underlying conception of sound as a physical entity that can or cannot move through a material depending on certain characteristics of the material. Even in the case of students explicitly associating the propagation of sound with energy transfer they might consider sound and/or energy as a substance that can propagate or be obstructed by certain materials.

> [Some materials attenuate sound more than others] because there are materials that allow the energy, which is transmitted by sound by means of the particles [of the medium], to go through them more than other materials

Therefore, as many authors evidenced in several previous research studies (Maurines 1993; Hrepic et al. 2010), the concept of sound as an entity instead of as a process is rather common.

As also illustrated in Table 2, most of the students (38%) accounted for sound attenuation in materials as being the difficulty for sound to be transmitted or the difficulty for particles of the medium to vibrate (C2). Students often associate this difficulty with certain modifications to the characteristics of sound waves. One of the changes to sound waves that students highlight is the ''decrease'' in energy, as exemplified by the following quote:

> The most porous materials are the most sound insulating materials because when a wave finds obstacles [within the material] it loses energy, and therefore the sound loses intensity

Some of the students that hold this conception C2 argue that sound transmission through different solid materials is more or less difficult depending on the distance between the particles of each material. The following student's quote evidences this type of conception:

> [Some materials attenuate sound more than others] because their particles are more separated and the vibration is transmitted worse than in a material whose particles are very close

According to Linder (1993), students generally consider that the distance between particles affects the speed of sound propagation, so that the smaller the intermolecular distance the faster the sound travels in the material. Students interpret that individual molecules of the material have to travel less distance to transfer sound to the next molecule. We interpret that students answer in terms of difficulty in sound transmission since they might conceive sound attenuation as a decrease in the speed of sound propagation in a medium. This conception would imply that the more sound is attenuated, the slower it propagates through a medium.

Remarkably, about 20% of students recognised sound absorption as a phenomenon that accounts for sound attenuation (C3), even though absorption was not explained in terms of energy dissipation. In some cases, students who explained sound attenuation as the absorption of sound within a material also evidenced a materialistic reasoning in terms of the entity or

Table 3 Characteristics that students associate with the acoustic behaviour of materials

Materials' capacity for attenuating sound is associated with …		Characteristic of materials	Number of students
Physical properties of materials (PPM)	Intensive (scale invariant)	Porosity	32/66 (48%)
		Density	29/66 (44%)
		Hardness	2/66 (3%)
	Extensive (dependent on the system size or the amount of material)	Thickness	5/66 (8%)
		Number of layers	4/66 (6%)
		Quantity of matter	5/66 (8%)
Internal structure of materials (ISM)		Distance between particles	5/66 (8%)
		Arrangement of particles	1/66 (2%)

particle model of sound. For instance, one student answered:

> If there is more material inside the box, it holds sound more, and thus, sound is heard less

According to the previous answer, sound is conceived as an entity that can be held or kept within the material.

Finally, it is worth noting that 15% of students considered both reflection and absorption as mechanisms of sound attenuation (C4), although in most of the cases they did not explain what they meant by absorption or relate it to energy dissipation.

Students' Conceptions of Acoustic Properties of Materials

From the subsample of students (66/72, 92%) that explained the differences in materials' capacity for attenuating sound in terms of their physical properties and/or internal structure (PPM and/or ISM respectively), we determined the characteristics that students associate with the acoustic behaviour of materials (Table 3).

As illustrated in Table 3, students mentioned several characteristics of materials as influencing their acoustic behaviour. The richness and variety of characteristics of materials mentioned by students is worth noting since they come from their inferences after the manipulation and observation of the three sound attenuating materials used in the experiment (rock wool, expanded polystyrene and glass wool). In particular, most of the students explained the differences in the materials' capacity for attenuating sound in terms of intensive properties, such as porosity, density, and hardness. Taking into account that porosity, density and elasticity are in fact the most relevant acoustic properties of materials (Hernández et al. 2011), this result is quite remarkable.

Furthermore, a sample of 33/72 (46%) students established relationships between certain physical properties or the internal structure of materials (categories PPM or ISM in Table 1) and acoustic behaviour of materials (ABM in Table 1). From these responses, we can determine that each property is conceived by different students as affecting the materials' capacity for attenuating sound in different ways. Table 4 presents the different roles attributed to different properties.

As illustrated in Table 4, all students who consider that sound is attenuated by materials that act as obstacles which do not allow sound to go through them (C1), also consider that sound attenuating materials are dense, not very porous and are formed by closer particles. On the other hand, students who state that sound attenuation in materials is produced when sound remains inside the material and does not get out (C3) believe that sound attenuating materials are porous. In this sense, we interpret that the acoustic role that students attribute to certain properties or the internal structure of materials is rather coherent with their conception of sound attenuation.

Concerning students who conceive sound attenuation as a phenomenon occurring while sound propagates within the material (C2), we evidence some differences in the roles that these students attribute to density. While some students consider that sound attenuating materials need to be dense so that their particles are difficult to move, other students state that sound attenuating materials should not be dense so that its particles are very separated from each other, and so they have more difficulty in transmitting sound. This last statement was also reported by Linder (1993), who found that many students consider that the density of materials uniquely depends on the distance between its particles, but not on the mass and packaging of particles.

Furthermore, we found that students use indistinctively specific properties of materials to describe them. In this way, several students do not only associate density with close proximity between particles, but they also consider that the terms dense, non-porous, and compact are equivalent

Table 4 Relationships between students' conceptions of sound attenuation in materials and the characteristics that they associate with acoustic behaviour of materials

Property	Conception of sound attenuation	Higher value of the property implies more capacity for attenuating sound		Higher value of the property implies less capacity for attenuating sound	
		Number of students	Students' quote	Number of students	Students' quote
Porosity	C1	–		2/33 (6%)	*"Materials with low porosity result in sound waves colliding [against them]"*
	C2	9/33 (27%)	*"More porous materials attenuate sound more since sound waves spend more energy when going through changes of medium"*	–	
	C3	3/33 (9%)	*"[Within porous materials] some phenomena occur. For instance, sound remains inside the pores, and so a great part of the sound is not transmitted to the opposite side"*	–	
	C4	3/33 (9%)	*"The more porous the material, the better the sound absorber it is"*	2/33 (6%)	*"The less porous the material, the better a sound reflector it is"*
Density	C1	4/33 (12%)	*"More dense materials result in sound waves colliding [against them]"*	–	
	C2	4/33 (12%)	*"The denser a material, the less vibration it allows in its particles and therefore it has more difficulty in transmitting sound"*	2/33 (6%)	*"If a material is denser, its particles are closer and therefore it transmits sound better than a less dense material"*
	C3	–		–	
	C4	2/33 (6%)	*"The denser a material, the more sound it reflects"*	1/33 (3%)	*"If the material has a low density, with lots of spaces between particles, it absorbs sound a lot"*
Distance between particles	C1	–		1/33 (3%)	*"Some materials have their particles very close and then air particles cannot go through them. In contrast, if the particles are more separated and allow air to enter the material then the vibrations will also nter [the material] and we can hear sound"*
	C2	3/33 (9%)	*"If particles are more separated, then the vibration is transmitted worse than in a material in which the particles are closer"*	–	
	C3	–		–	
	C4	1/33 (3%)	*"[If the material] has a lot of space between articles, it absorbs sound a lot"*	–	

Conclusions

The findings of this study provide evidence that students, who had been previously taught about the nature and propagation of sound and had measured the capacity for attenuating sound of different materials during a laboratory session, but who had not received any prior instruction on sound attenuation, were already able to elaborate on different types of—naïve or reasonable - explanations of sound attenuation. That is to say, there is evidence that students built some models of sound attenuation without explicit teaching on this topic, just having experience with materials with different acoustic absorption capacity.

Regarding the first research question, we could conclude that about one quarter of students conceptualise sound attenuating materials as sound barriers avoiding the passage of sound, and thus reflection is considered the only mechanism for sound attenuation. A smaller number of students recognise absorption as a mechanism of sound attenuation within a material. In any case, most of the students conceive the phenomenon of sound attenuation as the difficulty in transmitting sound in a material. In some cases, attenuation is conceived as being accompanied by the modification of the characteristics of sound waves. Remarkably, a small number of these students were able to relate sound attenuation to energy decrease.

The results of this study also provide evidence that students' preconceptions of sound attenuation reveal their conceptions of the nature and propagation of sound. In this sense, some students' responses show that the most common alternative conception is of sound as a physical substance that can go through a material or not depending on certain characteristics of the material. This conception corresponds to the well known "entity model of sound" described by Hrepic et al. (2010).

With regards to the second research question, the results of this study indicate that the role of the properties of a material and the role of the internal structure that students associate with its acoustic behaviour depend on their conceptions of sound attenuation. That is to say, the same material property can be conceived as a facilitator or an obstacle to absorb or to reflect sound, depending on the student's model of sound attenuation. Accordingly, the best sound attenuating materials are considered dense and nonporous by those students who think that sound attenuation is the result of the non-entrance of sound in a material. Sound attenuating materials are then conceived as sound barriers.

Furthermore, the findings also illustrate a lack of differentiation between certain properties of materials, such as density, compactness or porosity. The non-discrimination between certain scientific terms is a recurrent issue that needs plenty of attention.

Finally, the results of the present study also support previous research findings such as those reported by Linder (1993) concerning the oversimplification of the relationship between the density of materials and their microstructure (i.e. ''the smaller the distance between particles, the denser the material is'').

From this study, we conclude that students have a variety of preconceptions about sound attenuation and of the acoustic properties of materials, although some of them are more coherent from a scientific point of view than others. Thus, this research study supports the fact that students do not develop conceptual models that allow them to appropriately explain sound attenuation in materials as a mere result of their active engagement in designing and performing experiments in the REVIR session. The REVIR scenario, however, turned out to be a favourable context for allowing students to enrich and elicit their initial explanations.

Implications for Design

Within the research-based design paradigm, this study is relevant not only because it contributes to clarifying students' conceptions about sound attenuation and of the acoustic properties of materials, but also because the findings can be used to adjust and support the decisions made when designing a teaching sequence, like those already developed by Pintó et al. (2009) on the Acoustic Properties of Materials.

What Benefits Could There be of a Teaching Sequence on the Acoustic Properties of Materials?

Sound is an area of physics widely considered an essential component of most official science curricula. A traditional approach to the study of sound in secondary schools usually includes a macroscopic description of mechanical longitudinal waves in terms of its main characteristics (amplitude, frequency, etc.), and a microscopic description of the mechanisms involved in sound production, propagation and detection, such as vibration and the interaction between the particles of the medium.

Moreover, we can find relevant socioscientific issues related to sound, such as why we should avoid listening to and/or emitting loud music. Some authors (Sadler 2009) plead for the discussion of these issues in school science lessons in order to promote learning experiences that can affect students' thinking and the development of scientific literacy. In fact, linking sound with noise pollution has also become more common in curricula with an STS (Science- Technology-Society) or environmental education approach. To make students aware of this problem and more able to select the appropriate materials for practical soundproofing tasks, we designed a teaching/learning sequence drawn upon the findings presented here. The teaching sequence allows engaging students in the analysis of the relationship between the properties and internal structure of specific materials so that they are able to account for their acoustic behaviour. This meant tackling the study of sound from the perspective of Materials Science, emphasising the selection, testing and characterisation of the appropriate materials for noise control. This perspective is in agreement with Wendell and Lee's (2010) view, who consider that certain practices common to Materials Science, such as the characterization of materials by intensive properties, identification of the properties needed for particular purposes, and selection of existing materials with desirable properties, play an important role in young students' physical science learning.

What Have We Learned from this Study About the Teaching of this Topic that Could Contribute to the Design of a TLS on APM?

According to Scott et al. (2007), insights into how to teach conceptual content will only arise through design research, where insights into domain-specific reasoning are drawn upon in the design of teaching materials, which are then tested and developed in an iterative process (Lijnse 1995). According to this, we made detailed use of the above described students' preconceptions to the design of certain activities of the TLS on APM. Those activities are intended to facilitate students' eliciting of their own conceptions and make them yearn for a need for theoretical elements to justify their statements.

Considering the differences between the content to be taught (Hernández et al. 2011) and the students' conceptions evidenced in this study, we could establish the learning demands (Leach and Scott 2002) for 15–16 year-old students. These learning demands assume that the students involved come to:

- Understand the nature and propagation of sound as an event or process instead of as an entity.
- Conceive sound attenuation as a process of energy dissipation that involves reflection and absorption rather than an effect caused by materials when "hindering the entrance of sound" or "capturing sound".
- Appropriately conceptualize the acoustic properties of materials, at both macroscopic and microscopic levels, and relate them to the acoustic behaviour of materials. For instance, this would imply considering the density of solid materials as being related to the mass and packaging of their particles instead of associating it with the distance between particles.

Finally, the research study also gave us some insight into how to organise the content to be taught in the TLS on APM in order to facilitate students' development of a more coherent conceptual framework:

- Since students' conceptions of sound attenuation are influenced by their conceptions of the nature and propagation of sound, teaching about sound waves and their propagation should be a prerequisite of the TLS on APM.
- Similarly, since the properties and internal structure that students associate with the acoustic behaviour of materials is often based on their conceptions of sound attenuation in materials, we decided to develop their conceptions by distinguishing the mechanism of sound reflection from that of sound absorption. In this way, students would identify two types of sound attenuating materials (sound reflectors and sound absorbers) and would attribute different acoustic properties to them.
- As students tend to have a simplistic view of the relationship between properties and internal structure of materials, we decided to explicitly tackle these relationships by developing tasks and analogies to unambiguously develop students' understanding of the so-called acoustic properties of materials.

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Capítol 5

Publicació 2

L'article publicat a la revista *Physics Education* destaca la importància del disseny d'una seqüència d'ensenyament i aprenentatge que integri l'ensenyament de l'Acústica amb el de les propietats i estructura interna de la matèria en el context de la contaminació acústica i des d'una perspectiva de Ciència de Materials. En aquest article, s'explica la transposició didàctica del contingut a ensenyar i s'aprofundeix en el paper dels experiments que es porten a terme al llarg de la seqüència.

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Teaching acoustic properties of materials in secondary school: testing sound insulators

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Abstract
Teaching the acoustic properties of materials is a good way to teach physics concepts, extending them into the technological arena related to materials science. This article describes an innovative approach for teaching sound and acoustics in combination with sound insulating materials in secondary school (15–16-year-old students). Concerning the subject matter to be taught, a review of specialized literature on architectural acoustics and acoustic properties of materials is presented. A teaching/learning sequence on the acoustic properties of materials using a modelling and enquiry approach is introduced. A central experiment to test the capacity of sound attenuation of materials and to determine whether they behave as sound reflectors or sound absorbers is discussed in detail.

Introduction

Sound is a classic area of physics present in most official science curricula. A traditional approach to the study of sound in secondary school usually includes a macroscopic description of sound as a mechanical longitudinal wave in terms of its characteristics, and a microscopic description of the mechanisms involved in its production, propagation and detection, such as vibration and interaction of particles of the medium. Linking sound with noise pollution has also become rather common in curricula with an STS (science–technology–society) or environmental education approach [1] since noise has received increasing recognition as one of our critical environmental pollution problems. Beyond students' awareness and understanding of noise pollution as a social and scientific concern, we consider that involving students in the process of problem-solving and evaluation of the appropriateness of possible soundproofing solutions is also a desirable teaching goal that needs to be accompanied by a robust understanding of the mechanisms of sound propagation and attenuation.

This focus on noise pollution and its possible solutions implies tackling the teaching of sound from a technological perspective, emphasizing the selection, testing and characterization of appropriate materials for noise control. Some of these materials have been investigated and developed within one of the most active areas of research, which has found applicability in a wide range of societal concerns: materials science. This discipline is considered to encompass both science and engineering but is essentially an interdisciplinary field, bringing together elements of applied physics and chemistry and extending them into the technological arena.

Despite being such an active field, the presence of materials science in school science curricula is rare. Generally, it is limited to technological approaches instead of scientific analyses. With the intention of reducing the gap between materials science and school science taught in secondary school, we decided to tackle the study of sound and acoustics in combination with sound insulating materials.

The emphasis on acoustics in teaching is not new. More than 40 years ago, Lindsay [2] claimed that, 'in view of the importance of sound in the life of all of us, it would be desirable that every young person had brought to his attention at an early age the fundamental ideas of acoustics [· · ·], becoming acquainted with sound attenuation or with the peculiarities of indoor sound'. What is not so common is the teaching emphasis on practices common to materials science, such as characterizing materials by intensive properties, identifying the properties needed for particular tasks, and selecting existing materials with desired properties, which are highlighted by Wendell and Lee [3] as 'playing an important role in young students' physical science learning'. The most innovative aspect of the teaching approach that we propose consists of engaging students in analysing the relationship between properties and internal structure of specific materials so that they are able to account for the acoustic behavior of these materials concerning sound attenuation and to select appropriate materials for practical soundproofing tasks.

The aforementioned implies integrating the study of sound and matter, which in the Spanish educational context are considered as two independent topics that are included in the official 'physics and chemistry' syllabus for the last year of compulsory secondary school. The official document states that students should be able to do the following.

- Characterize sound waves in terms of amplitude, frequency, period and wavelength; identify phenomena related to sound reflection; and justify healthy measures to listen to music.
- Observe properties of materials and sort materials in terms of properties; establish relationships between the physical properties and structure of materials.

Aiming at further interrelating these topics, we designed and iteratively developed (evaluated and refined on the basis of several classroom implementations) a teaching–learning sequence (TLS), called acoustic properties of materials [4], intended for 15–16-year-old students.

What should we teach about sound attenuation and acoustic properties of materials?

For our purpose of taking a technological approach to the sequence and our attempt to introduce ideas of materials science in the designed curriculum, we *educationally reconstructed* [5] the contents to be taught, using diverse specialized sources [6] and making these contents significant for 15–16-year-old students. We were particularly interested in the specialized literature on environmental noise control and architectural acoustics in order to understand how the sound environment in rooms and buildings of all types can be optimized or avoided, depending on the acoustical needs of such spaces. On the other hand, we wanted to find out what research tells us about the characteristics of materials that play a significant role in their acoustic behaviour. This section is intended to present the main ideas resulting from the literature review and the educational reconstruction of the contents to be taught in science classes for the last compulsory year of secondary school.

Sound attenuation

The study of the acoustics of a room may be concerned with sounds which are produced inside or outside a room. Sounds which are produced outside a certain room are normally undesired in the room and sounds which are produced inside a room may also be undesired for people outside the room. In any case, the problem is one of soundproofing, also called sound attenuation or sound insulation, to reduce the intensity of the sound propagating into or out from the room. When the sounds generated in a room need to be perceived in optimal acoustic conditions, then the problem is one of acoustic treatment to adjust the acoustical characteristics of the room. Focusing on sound attenuation, the solution for a problem of noise pollution requires analysis of two processes.

(i) Sound attenuation through a single medium (e.g. air).
As sound waves spread spherically from the sound source, the energy is distributed along an area that grows larger and larger, and so the energy that is transmitted through a unit of area per second (intensity) is less and less. This decrease of sound intensity level with distance from the source does not take into account the absorption produced in the medium; it is purely due to the geometrical distribution of the energy. Nevertheless, the energy is also dissipated when sound propagates through a single medium. In the words of Lawrence [7], 'the "sounding" has in the end warmed up the surroundings'.

(ii) Sound attenuation at the interface between two media (e.g. air and the material that forms the walls of a room).
The literature consulted generally presents sound attenuation as the combined effect of scattering and absorption produced by materials, which weakens sound further than the mere propagation of sound when it spreads through a medium. Scattering is the reflection of the sound in multiple directions due to irregularities of the object that sound reaches. Absorption is understood as the energy dissipation within a single medium. In the teaching approach designed, sound attenuation is also described microscopically as the process by which the particles of a medium, which were previously vibrating with a certain amplitude as a result of the interaction with other particles, later do not move as much, whereas others move more, and in a more disordered way.

According to the agreed definition of sound attenuation in materials as the combined effect of reflection and absorption, two types of sound-attenuating materials can be distinguished depending on the mechanism of sound attenuation that predominates: sound-reflecting materials[1] and sound-absorbing materials. The next section specifically deals with the acoustic characteristics of these materials.

Acoustic properties of materials
Understanding the variables that affect sound attenuation is the first step to be able to control these variables when designing and selecting appropriate solutions for soundproofing and acoustic treatment. In this sense, analyzing the influence of the so-called acoustic properties of materials on their acoustic behaviour would allow the choice of specific materials for particular requirements. At this point it is worth discussing the term 'acoustic' properties of materials since, as stated by Muehleisen [8], 'it is a term open to interpretation'. Distinguishing between macroproperties and properties related to the internal structure of materials, we proceed to classify the acoustic properties of materials[2] reported in the literature consulted.

Acoustic macroproperties. One common magnitude is generally mentioned as a property of materials that affect sound attenuation: acoustic impedance. Acoustic impedance is a magnitude that plays a relevant role in determining sound

[1] Although this term is not as widely used as the term *sound absorbing materials* in specialized literature, we decided to name those sound attenuating materials that mainly reflect the sound that reaches them *sound-reflecting materials* (or sound reflectors). This decision was taken after finding that the term *sound insulator* was misleading, used in some cases to mean sound-reflecting material whereas in other cases to mean any material that significantly attenuates sound.
[2] The designed sequence emphasizes the difference between materials and objects so that thickness and shape are associated with objects whereas the intensive properties are associated with materials.

transmission and reflection at the boundary between two different media. Sound reflection only occurs when sound reaches the interface between two materials with different characteristic acoustic impedances. The difference in acoustic impedance is commonly referred to in specialized literature as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the boundary between the two media.

When the acoustic impedances of the materials (1, 2) on the two sides of the boundary are different, the fraction of the incident sound wave that is reflected *(R)* is calculated using the equation

$$R = \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^2$$

The value resulting from this calculation is known as the reflection coefficient. Multiplying the reflection coefficient by 100 yields the amount of energy reflected as a percentage of the original energy. According to the principle of energy conservation, the amount of reflected energy plus the transmitted energy equals the total amount of incident energy, and thus the transmission coefficient is calculated by simply subtracting the reflection coefficient from one $(T = 1 - R)$.

The relationship expressed by the previous equation also indicates that the reflection coefficient does not differ depending on whether material 1 has higher or lower acoustic impedance than material 2. That means that the amount of reflected energy when sound propagates from air to a solid material is the same as the amount of reflected energy when sound propagates from the same solid material to air.

The acoustic impedance *(Z)* of a material is defined as the product of its density (ρ) and the acoustic velocity *(v)* in the material:

$$Z = \rho v.$$

Since the acoustic velocity or speed of sound propagation through a certain medium is generally defined as

$$v = \sqrt{\frac{k}{\rho}}$$

(k being the elastic modulus), then the acoustic impedance could be redefined as

$$Z = \sqrt{\rho \cdot k}$$

This last equation summarizes the dependence of the acoustic impedance upon two essential bulk[3] properties of the material medium through which the sound wave is travelling: elastic and inertial properties. In particular, these properties are discussed in the designed sequence as follows.

- Elastic properties are related to the tendency of a material to maintain its shape and not deform whenever a force or stress is applied to it. The designed sequence characterizes materials according to their elasticity distinguishing rigid materials (high elasticity or high elastic modulus k) from flexible materials (low elasticity or low elastic modulus k).
- Inertial properties are related to the object's tendency to change its state of motion. The density of a material (ρ) is the magnitude related to inertia.

Rephrasing the idea of impedance mismatch in our educational reconstruction, we can consider that the greater the difference between density and elasticity of two media, the greater the percentage of energy that will be reflected and the lesser the percentage of energy that will be transferred to the material when sound reaches the interface. Therefore, very elastic and dense materials usually behave as good sound reflectors that attenuate sound that reaches them from the air. In contrast, sound absorbers are usually less elastic and dense and, therefore, behave as bad sound reflectors.

[3] A bulk or intensive property of a material is considered a physical property that does not depend on the size of an object made of that material or the amount of material. In other words, it is scale invariant.

Acoustic properties related to the internal structure. The properties related to the internal structure of materials are associated with the emergence of physical properties. With the purpose of establishing links between physical properties and internal structure of materials, we need to discuss elasticity and density at a microscopic level. In our teaching approach for the intended educational level, elasticity is characterized by the strength of the attractions among atoms and/or molecules whereas density is characterized in terms of the inertial mass and packing of particles. According to this, the greater the strength of the interactions among the particles or the greater the inertia of the particles of a medium, the less responsive they will be to the interactions with neighbouring particles.

Apart from density and elasticity, which actually affect the acoustic behaviour of materials, the effect of porosity is also recognized as a property of materials that affects sound absorption. Porosity is related to the presence of air particles inside the pores of a material, which in turn is formed by different particles. When sound reaches a porous material, it is mainly absorbed. In other words, porous materials usually behave as good sound absorbers but bad sound reflectors. In our qualitative description of the phenomenon, this effect is explained in terms of the friction between the air inside the material (within the pores, between fibres) and the solid walls (or skeleton) of the material. Moreover, when sound propagates within a porous material, it is reflected many times because there are several air–solid–air interfaces. Due to friction and to the multiple reflections within the pores, part of the energy associated with sound is transferred to the solid skeleton of the material by making its particles vibrate and therefore it is dissipated.

A more sophisticated view of porosity as an acoustic property would include some details concerning the size of the pores and would relate the absorbing capacity of porous materials to the frequency of sound since absorption is frequency-dependent. Even though the soundproofing of a room would need to take into account those and other factors that play a role in sound attenuation (e.g. the shape of the surface of plates made of a certain material, thickness of the plates, etc), we consider that the level of the students to whom the designed sequence is addressed and the complexity of the topic are weighty reasons to limit the sequence to the study of the properties of materials that affect their acoustic behaviour: density, elasticity and porosity, as described above.

A proposal to teach acoustic properties of materials to secondary school students

The teaching/learning sequence on acoustic properties of materials

The designed sequence on acoustic properties of materials is intended to promote students' engagement in their own process of development of coherent conceptual models that allow them to predict and explain: (i) sound attenuation through materials in terms of energy, and (ii) the acoustic behaviour of sound reflectors and sound absorbers in terms of their physical properties and (iii) in terms of their internal structure.

This emphasis on modelling is mediated by an enquiry approach so that the designed sequence prompts students to elicit, build, use, compare, evaluate and refine conceptual models and, while doing this, students are also expected to actively ask questions, reflect on, design and perform experiments and strategies to solve particular problems through actual scientific practices. In brief, we agree with Viennot [9] that enquirybased science learning should focus on promoting 'students' conceptual achievement and intellectual satisfaction beyond mere excitement'.

A case that often appears in the news related to an action brought by a community of neighbours against a pub's owner because of the noise was chosen as an authentic activity context that would require students to apply their knowledge to situations similar to those that they could encounter in the world outside the classroom. Key leading/teaching questions are provided to make students reflect on what they already know about the topic and where each task should be leading them. These teaching questions are structured within three main units around the conceptual models that are intended to be developed and applied by students in the activities of the sequence.

The sequence of activities and the main leading questions of each unit of the sequence are described in table 1.

An experiment to test sound insulating materials

A central experiment was used throughout the sequence with different teaching goals depending on the learning stage.

- In Unit 1, students are asked to design and perform an experiment to determine how much sound is attenuated by a certain material or object, after having developed a more sophisticated model of sound attenuation which includes both reflection and absorption.
- In Unit 2, the experiment is of central importance for the refinement of a conceptual model that would allow students to predict and explain the acoustic behaviour of sound reflectors and sound absorbers in terms of their physical properties. Students are directed to design and perform an experiment to determine the acoustic behaviour (as a sound reflector or as a sound absorber) of various materials. This test allows them to classify a set of materials according to their acoustic behaviour and then to infer properties that all sound reflectors have in common and properties that all sound absorbers have in common.
- In Unit 3, students are asked to select the most suitable materials to soundproof and acoustically treat the disco, and to justify their selection. We ask that the choice and its justification be explicitly based on empirical evidence and conceptual models.

The experimental setup used throughout the designed sequence in the investigations carried out by students can be prepared using standard materials. The main elements of this setup are the *sound source*, the *sample of material* and the *detector*.

Regarding the source, teachers and students were provided with broadband buzzers like the one shown in figure 1, which were connected to 3 V batteries and emitted a 4500 Hz (fundamental frequency) sound at a constant intensity level. Depending on the age and background of the students, the appropriateness of the use of a buzzer to experiment on the actual effects that take place in a disco related to intensity and frequency of sound could be discussed. In particular, the sound emitted by the buzzer is similar to the music played in a disco in that it does not emit a pure tone but is composed of multiple sounds with different frequencies. Therefore, as in a disco certain frequencies (usually high) are more easily attenuated than others depending on the properties of the materials used to cover the walls of the box. In some cases, students saved an audio file with similar characteristics (sound with constant intensity level and frequency) in their mobile phones and the sound was reproduced using the phone's loudspeaker.

The samples or plates of material are contained inside a cardboard box covering all six sides. The cardboard box itself represents the structure of a room or closed space, which has a particular geometry, whose walls, floor and ceiling are not covered with any extra material but are made of building and construction materials. The plates of material covering the box (as shown in figure 2) represent the samples of the material that could be used to soundproof a certain room. These samples have similar thicknesses (2.5 ± 0.5 cm) to allow comparison of the capacity of sound attenuation of different materials instead of the effect due to the different thicknesses of the plates.

Table 1. Description of leading questions and activities corresponding to each unit of the designed sequence.

Unit	Activities
1 Sound–material interaction	*1.1 What acoustic problems arise from a disco located in a residential neighbourhood?* • Exploration and discussion of the context of the sequence and the problem to be solved • Eliciting preliminary conceptions of sound propagation through different media *1.2 Why can sound reach any corner of the dance floor?* • Eliciting preliminary conceptions of sound reflection and reverberation • Exploration and interpretation of data, graphs and images on sound reflection and reverberation • Application of the refined conceptions in other activities *1.3 How can we manage to avoid hearing too much sound outside the disco?* • Eliciting preliminary conceptions of sound attenuation • Introduction of the scientific point of view concerning sound attenuation • Interpretation of the acoustic behaviour of two materials (sound reflector and sound absorber) using two diagrams that represent the distribution of energy (reflected, absorbed, transmitted) of an incident sound caused by each type of material • Design and implementation of an experiment to determine how much sound is attenuated by a certain material • Structuring of ideas in answering a question about soundproofing
2 Properties and internal structure of sound reflectors and sound absorbers	*2.1 Which characteristics does a good sound reflector have? And a good sound absorber?* • Eliciting preliminary ideas on the physical properties and internal structure of sound reflectors and sound absorbers • Prediction of the acoustic behaviour of several materials on the basis of their properties • Design and implementation of an experiment to determine whether each of the previous materials behaves as a sound reflector or as a sound absorber • Classification of the tested materials in sound reflectors and sound absorbers on the basis of the empirical results • Description of the physical properties of the tested materials on the basis of their observations • Identification of the physical properties that all the tested sound reflectors have in common (and the ones that all the tested sound absorbers have in common) • Prediction of the acoustic behaviour of some materials in terms of their physical properties *2.2 How can we explain that the properties of a material affect its acoustic behaviour?* • Interpretation of how sound reflectors and sound absorbers are internally configured using an analogy • Interpretation of mechanisms of sound attenuation in materials according to their internal structure • Explanation of the mechanisms of sound attenuation of specific materials in terms of their acoustic properties and internal structure
3 Acoustic treatment and soundproofing	*3.1 Comparing materials. Which one could be used to soundproof the disco?* • Engagement in a decision-making process to solve the original problem of the disco and justify the solution on the basis on experimental findings and developed conceptual models

Figure 1. Buzzer connected to a 3 V battery.

Several boxes were covered with plates made of different materials[4].

As detectors, we used sensors to measure sound intensity level, known as sound level meters[5], which are the common instruments used in real life for noise control. Sound level meters can also be used in connection with data capture systems (MBL technology) and computers (figure 3) in order to register and graph in real time the evolution of sound intensity level during the experiments (figure 4).

[4] The materials that form the plates used to cover each box are chipboard and Formica, aluminum foil, expanded polystyrene, cork, foam, glass wool, felt, polyurethane foam, rock wool, felt and rubber. Samples of these materials are available in DIY shops.

[5] The sound level meters that we used are from Vernier and their cost is about 160 e, but they are also available in teaching resource centres. Moreover, in the Catalan context, MBL technology has been provided to all state secondary schools by the Catalan Government.

Figure 2. Cardboard boxes and their lids covered with glass wool and polyurethane foam, respectively.

Figure 3. Experimental setup (sound level meter-MBL interface-computer, box and lid covered with chipboard-Formica, buzzer inside the box).

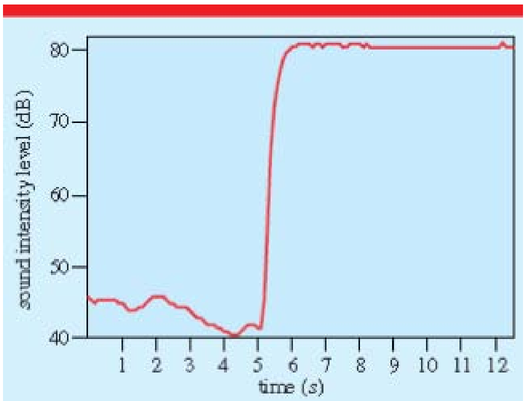

Figure 4. Graph showing sound intensity level corresponding to environmental noise (40–45 dB) for the initial 5 s and the sudden increase in sound intensity level (up to 80 dB) when a buzzer located 30 cm from the sound level meter is turned on.

The experiment carried out by students throughout the designed sequence consists of using the sound level meter to measure the sound intensity level produced by the sound source that has been placed inside a box whose walls have been covered with a particular material (sample). Depending on the test to be carried out by the students (testing the capacity of sound attenuation of certain materials or determining the acoustic behaviour of these materials), the sound intensity level needs to be measured outside or inside the box.

If students need to measure how much sound attenuation is produced by a certain material (at a certain distance from the source), a possible procedure consists of placing the sound level meter outside the box covered with that material (figure 5). In this way, students could measure the sound intensity level transmitted outside the box covered with the tested material (see the third column of table 2 as an example), which represents the noise control measurement that would be taken at a neighbours' house. Nevertheless, if the aim is to calculate how much sound has been attenuated, students need to compare the measurement outside the box with a reference value, also measured outside the box at exactly the same distance as the previous measurement but when the box is not covered inside with any material (see the first value of the third column of table 2 as an example).

On the other hand, if the purpose is to determine whether the acoustic behaviour of a certain material corresponds to a sound reflector or a sound absorber, then the sound intensity level should be measured inside the box (figure 6; see the fourth column of table 2 as an example) where the sound source is, which would be an equivalent situation to testing inside the disco if the materials placed on the walls mainly reflect or absorb sound. For this purpose, one of the walls of each box has a small hole[6] to allow introduction of the microphone of the sound level meter inside the box.

[6] When measuring outside the box, the hole was usually covered with the hand or with a piece of the same material as that covering the box. When the hole was not covered, the sound level meter was placed at the opposite side of the box and the variations of the measurements of sound intensity level outside the box due to diffraction from the hole ranged between 0.5 and 1 dB; thus they are not considered significant.

Figure 5. Experiment to test the capacity of sound attenuation produced by the material inside the box.

Figure 6. Experiment to determine the acoustic behaviour of the material inside the box.

Again, the first measurement that should be taken is the sound intensity level inside the box when it is not covered with any material at a certain (controlled) distance from the source (see the first value of the fourth column of table 2 as an example). This measurement would correspond to the reference value for this experiment. Once the box is covered inside with a certain material, if the sound intensity level measured inside the box is higher than the reference value, then we can conclude that the material behaves as a sound reflector. If the measured value is lower than the reference value, we can conclude that the material behaves as a sound absorber.

As an example, table 2 shows the values obtained measuring outside and inside boxes covered with different materials together with a description of the physical properties of each material and their acoustic behaviour (according to the measurements).

The previous measurements allow comparison of the relative capacities of sound attenuation of different materials by comparing the values of sound intensity level outside each box (if the plates of each material have similar thickness and the distance between the sound source and the sound level meter has been kept constant for every measurement). Moreover, these data allow comparison of the values of sound intensity level measured inside the box with the corresponding reference value (inside the box) to determine whether each material behaves as a sound reflector or as a sound absorber. The fact that two different source–detector distances have been considered does not affect the conclusions that can be drawn from the collected data since comparison was made, on the one hand, of the values outside the box with each other and with the reference value outside the box and, on the other hand, of the values inside the box with the reference value inside the empty box. Once the students have carried out the experiments described above and obtained the same or similar measurements to those presented in table 2, they are expected to make informed decisions on the materials that should be chosen to propose soundproofing solutions for the noise control of a room.

Summary and implications

In this article, we have described an innovative approach to integrating the teaching of sound and properties and structure of matter in secondary school, focusing on practices distinctive to materials science, such as characterizing materials by intensive properties, identifying the properties needed for

Table 2. Sound intensity levels measured outside and inside boxes covered with different materials, description of each material and their acoustic behaviour.

Material	Description	Sound intensity level outside [a] the box (dB)	Sound intensity level inside [b] the box (dB)	Acoustic behaviour
Empty box	Reference values	80.5 ± 0.5	92.5 ± 0.5	—
Chipboard and Formica	High density (0.70 g cm−3), high rigidity, no porosity (Formica), Little porosity (chipboard)	64.5 ± 0.5	109.5 ± 0.5	Sound reflector
Aluminum foil [c]	High density (2.70 g cm−3), high rigidity, no porosity	71.5 ± 0.5	99.5 ± 0.5	Sound reflector
Expanded polystyrene	Low density (0.02 g cm−3), low rigidity, no porosity (non-connected open pores)	64.5 ± 0.5	93.5 ± 0.5	Sound reflector
Cork	High density (0.29 g cm−3), high rigidity, little porosity	70.5 ± 0.5	81.5 ± 0.5	Sound absorber
Foam	Low density (0.03 g cm−3), low rigidity, porosity (large pores)	67.5 ± 0.5	78.5 ± 0.5	Sound absorber
Glass wool	Low density (0.02 g cm−3), low rigidity, porosity	57.5 ± 0.5	69.5 ± 0.5	Sound absorber
Felt	Low density (0.07 g cm−3), low rigidity, porosity	53.5 ± 0.5	67.5 ± 0.5	Sound absorber
Polyurethane foam	Low density (0.13 g cm−3), low rigidity, porosity	55.5 ± 0.5	66.5 ± 0.5	Sound absorber
Rock wool	Low density (0.06 g cm−3), low rigidity, porosity	50.5 ± 0.5	64.5 ± 0.5	Sound absorber
Felt and rubber	Low density (0.21 g cm−3), low rigidity, porosity (felt), no porosity (rubber)	48.5 ± 0.5	59.5 ± 0.5	Sound insulator (sound absorber + sound reflector)

[a] Source–detector distance: 30 cm. [b] Source–detector distance: 20 cm.
[c] Aluminum foil was used to determine the acoustic behaviour of the aluminum but not to compare the capacity of sound attenuation of this material with other materials' capacities since only one layer of aluminum foil was used to cover a box, hence the thickness of the plate was not comparable with the rest. Nevertheless, here we also provide the measurement obtained when measuring outside the box covered with one layer of aluminum foil.

particular tasks, and selecting existing materials with desired properties. The teaching approach has been realized by designing a teaching/learning sequence on acoustic properties of materials, which is available for anyone who wishes to use it.

The review of specialized literature and the consequent educational reconstruction of the contents to be significantly taught in the last year of compulsory secondary school has been detailed to clarify the main mechanisms that intervene in sound attenuation (sound reflection and sound absorption) and the properties of materials that affect their acoustic behavior or 'acoustic properties' (density, elasticity and porosity).

The structure and approach of the activity sequence designed, and the central experiment specifically designed to support students' modeling processes and enquiry practices in the science classroom, have been described in detail. This exhaustive description of the experiment is given to allow other teachers and students to use it in a teaching/learning sequence like the one presented here, or for independent research work. In our context, in addition to implementation with 15–16-year-old students in a school setting, this experimental setup has also been used productively by other high school students to carry out investigations on the effect of different frequencies of sound or different thicknesses of plates on the capacities of sound attenuation of the tested materials.

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Capítol 6

Publicació 3

El capítol del llibre editat per *Springer* presenta un estudi de cas sobre el procés de disseny, implementació i refinament iteratiu de la seqüència d'ensenyament i aprenentatge sobre propietats acústiques dels materials. En definitiva, aquest capítol aborda el tema del desenvolupament iteratiu de la SEA dissenyada al llarg de diverses iteracions amb l'objectiu de amb millorar progressivament la seva qualitat, sent aquesta definida en termes de la validesa, la utilitat i l'eficàcia (Nieveen, 2009).

Al llarg del desenvolupament iteratiu, s'han identificat els aspectes problemàtics de la SEA al llarg de les consecutives implementacions a classe, s'han analitzat els diversos tipus de canvis introduïts per superar les dificultats d'alumnes i professors i s'han interpretat les raons crítiques per introduir aquests canvis. De tots aquests resultats dóna compte el present capítol.

The Process of Iterative Development of a Teaching/Learning Sequence on Acoustic Properties of Materials

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Abstract This chapter describes a case study of the process of design, implementation and refinement of an innovative teaching/learning sequence (TLS) aimed at 10th graders (15–16 year-old students) that deals with sound attenuation using different materials. The theoretical framework used to guide the design of the sequence structure, the selection of contents and the pedagogical approach are described. This chapter also reports the development of the teaching/learning sequence, carried out throughout two cycles of field testing to gradually improve the efficacy of the sequence in promoting better performance in students. Throughout this iterative development, we identified the problematic aspects of the sequence during its classroom implementation, analysed the types of changes introduced to overcome students' and teachers' difficulties using the sequence, and the critical reasons for those changes.

1. Introduction

Within the field of Science Education, several research-based instructional assignments and approaches for improving students' understanding of scientific knowledge have been developed over recent decades (Méheut & Psillos, 2004). Furthermore, sound theoretical frameworks and methodological tools have been elaborated to guide the design and validation of teaching/learning sequences (TLS), e.g., Didactical Structures (Lijnse, 1995); Learning Demands (Leach & Scott, 2002); Teaching Experiments (Komorek & Duit, 2004); Model of Educational Reconstruction (Duit, Gropengießer, & Kattmann, 2005). The main aim of all these approaches consists of "reducing the uncertainty of decision making in designing and evaluating educational interventions" (van den Akker, 1999, p. 5).

Like many other researchers in the field of science education, when we begin a research study, we are guided by diverse aims such as the applicability and efficacy of its results in particular classroom contexts or the attention to the changing needs that teachers face when a new syllabus or reform policy are introduced. In addition, when we decide to elaborate an innovation based on research results (e.g., a TLS) that fulfils those requirements, we also intend to contribute to the existing theoretical and methodological frameworks. These are some of the main reasons to initiate and conduct design-based research.[1]

One of the most common agreements among most of the different approaches to design-based research (Lijnse, 1995; Design-Based Research Collective, 2003) is the fact that the development process of any innovative intervention should be iterative or cyclical as it involves different stages, such as design, implementation, analysis, evaluation and redesign, enlightened by research data, in order to achieve an appropriate balance between intended learning objectives and learning outcomes. We agree with van den Akker (1999, p. 9) when he states that "direct application of [pedagogical] theory is not sufficient to solve many complicated practical problems, so an iterative process of "successive approximation" or "evolutionary prototyping" of the "ideal" intervention is desirable". Lijnse and Klaassen (2004, p. 538) also argue that "the application of general (learning) theories results in heuristic rules that simply cannot guarantee that the teaching process that is supposed to be governed by them will have the necessary didactical quality". We agree with these authors about the need to search for evidence of good ways of teaching a certain topic and to discuss the didactical quality of an innovation (e.g., an innovative TLS dealing both in content and pedagogical approach).

Although several publications have reported the design and evaluation of an innovative TLS on a certain topic, not many empirical studies have reported relevant details of the process of refinement of a TLS analysing the different changes that this development process entails, and thus suggesting further ways to overcome the identified weak points or flaws of the designed sequence. Our perspective is that more in-depth research studies are necessary to provide compelling insight into how to refine a sequence so that this process is not undertaken via intuition but is based on research results.

[1] We adopt this term in a broad sense to refer to various kinds of research approaches that are related to design, development and evaluation of educational interventions, programmes, processes and products (Design research, Development / Developmental research, etc).

With the intention of contributing to an understanding of these issues, we have carried out a research study describing, analysing and interpreting the process of iterative development of a TLS on Acoustic Properties of Materials (APM).

2. Context

The design and development of a TLS on APM was carried out during three consecutive years (2007–2009) by three researchers in science education and six experienced secondary school teachers (one physics graduate and five chemistry graduates) from four different schools. The researchers and teachers collaborated actively as part of a community of practice (Wenger, 1998), called a "local working group" (LWG), while engaged in the design of educational materials.

Most of the secondary school teachers who engaged in the group had certain previous experience in educational materials development and some of them are enrolled in continuous professional development courses. The main reasons to opt for strong university–school collaboration for the development of the sequence were the focus on learning on the part of all the members of the community of practice (see Chapter 5) and the intention to avoid critical transformations of the innovation when implementing it. Relevant studies (Pintó, 2005; Viennot, Chauvet, Colin, & Rebmann, 2005) have actually shown that a passive role on the part of teachers when designing an innovation might have deep implications for its implementation, often leading to a distortion of its rationale in a critical way.

The local working group evolved during the three years not only as regards the expertise of the members but also as regards the number of people, since new secondary school teachers, who were colleagues of the previous teachers, decided to become part of the group at some stage of the process of development of the TLS.

During the design of the TLS, all the members of the established LWG collaborated actively in periodic face-to-face meetings and by means of an online platform. In an initial stage, a preliminary content structure for the sequence was decided among the LWG members. The role of the researchers consisted of: (i) guaranteeing that the specific learning targets[2] that each task pursues are explicit; (ii) carrying out the didactical transposition of the contents; and (iii) suggesting the didactical approach to be introduced in the material (mainly the model-based inquiry approach) and the experimental setting. These three goals were quite innovative for the teachers involved in the LWG. Nevertheless, any decision was discussed and agreed with the teachers during the LWG meetings with the purpose of promoting teachers' sense of ownership of the innovation (Ogborn, 2002). During these meetings, the teachers also provided useful remarks about students' skills, background and real classroom contexts, which allowed the guidance provided to students to be adapted. In short, teachers and researchers worked together at the core of designing the assignments and the assessment tasks of the sequence.[3] During the refinement of the TLS, all the members of the LWG also collaborated in discussing possible flaws of the material and suggesting changes to refine the first version of the material.

The designed TLS on APM was planned to be implemented in ordinary schools with 10th graders (15–16 year-old students) within the science subject "physics and chemistry". In the Spanish educational context 10th grade is the last compulsory academic year for students under 16 years old and it is also the first grade in which the study of physics and chemistry is optional. The official science syllabus in our context for the last year of compulsory secondary school, which suggests a qualitative and phenomenological study of the contents, includes the following main topics: sound waves, and structure and properties of matter, among other topics. Each of these topics includes a number of subtopics detailed in Table 1:

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[2] These are expressed in a very specific and measurable format and the attainment of them can be determined within a given sequence or lesson. These are usually formulated: "Students are expected to be able …"

[3] Pintó et al., (2009) *Acoustic Properties of Materials*.

Table 1: Description of some topics included in the Catalan official science syllabus

Topic	Subtopics
Sound waves	Characteristics of sound waves, Propagation of sound waves, Phenomena related to sound such as reflection, Sound production, Hearing
Structure and properties of matter	Particulate nature of matter, Atomic structure, Atoms and molecules, Relationship between properties and structure of materials

Most of the aforementioned subtopics of sound and properties of matter were studied before the implementation of the innovative sequence on APM as pre-requisites for it.

Nevertheless, this sequence represented an innovation for the teachers involved in the design and implementation of the sequence since it integrates the aforementioned topics in the study of the acoustic behaviour of materials related to their properties and internal structure. Moreover, the sequence also meant a challenge for the teachers with regard to the didactical approach. Although all the teachers in our context are used to encouraging students to work in groups to a greater or lesser extent, most of them were interested in learning different teaching strategies to promote more effective engagement and learning in students. The experimental tasks proposed in the sequence meant a minor challenge for teachers and students since all of them are familiar with the use of data capture systems and related software although the specific sensor that was used (sound level meter) represented a novelty for them.

The local educational culture facilitated the development and introduction of these innovations since teachers are constantly encouraged by professional development programmes or other organizational structures to experiment with different teaching strategies and to use a variety of materials and resources. Furthermore, teachers have autonomy to introduce the changes that they consider necessary in their classes.

3. Design of a teaching / learning sequence on Acoustic Properties of Materials

3.1 Theoretical framework for the design of the sequence

3.1.1 Elicitation of design principles

As Kali, Levin-Peled and Judy (2009) state, curriculum development is based on the epistemological views of the designers. Designers make epistemological assumptions about the nature of knowledge in a specific scientific domain and about how learning takes place, which stem from theories or perspectives on learning. Several epistemological assumptions were discussed and taken into account when designing conditions to promote students' learning with understanding of the topic of acoustic properties of materials. Hereafter, the explicit guidelines based on theoretical assumptions and empirical arguments that were used to orient the design of the TLS on APM are called design principles.

With the purpose of informing the design of the TLS on APM, we drew on the Two Worlds framework, stated by Buty, Tiberghien and Le Maréchal, (2004). The epistemological hypothesis underpinning this framework is that modelling processes play a central part in understanding science by relating descriptions of objects and events in the material world to the world of theories and models. Everyday knowledge and scientific knowledge offer ideas and languages for describing objects and events of the material world; these are linked via modelling processes to distinctive theories and models for interpreting, predicting, or explaining events in the material world. As stated by Tiberghien, "the distinction between the world of theories/models and the world of objects/events serves to make explicit the modelling processes that establish relationships between them" (Ruthven, Laborde, Leach, & Tiberghien, 2009, p. 335). Drawing upon the Two Worlds framework, the TLS on APM was designed to help students move from descriptions of objects and events towards explanations in terms of models and theories, from everyday knowledge towards the perspective taken by science. Thus, modelling is considered a key scientific practice and hence the designed sequence is intended to promote students' engagement in their own process of development of coherent conceptual models.[4]

This emphasis on modelling is mediated by an inquiry approach so that the designed sequence proposes not only that students elicit, build, use, compare, evaluate and refine conceptual models, but also that they ask questions, reflect on, design and perform experiments and strategies to solve particular problems. This approach, called model-based inquiry by Windschitl, Thompson and Braaten (2008), is grounded on the idea that "the particular practices that are integral to the core work of science are organized around the development of evidence-based explanations of the way the natural world works" (p. 943). Accordingly, the scientific practices promoted in the designed sequence do not merely refer to simple manipulative tasks but they involve thinking / reasoning strategies, which can be complex and demanding for many students. For this reason, providing students with gradual scaffolding throughout the activities of the sequence, depending on how familiar students are with certain practices, tools or contents, becomes necessary to support students' modelling and development of inquiry skills.

On the other hand, the TLS on APM was drawn upon a problem-posing approach, providing students with a series of key questions contextualized around a certain scenario (soundproofing and acoustic treatment of a disco). According to Lijnse (2005), the emphasis of a problem-posing approach is not merely on engaging students in the process of solving a certain problem, but rather on experiencing a content-related sense of purpose and on coming to see the point of developing their existing conceptual knowledge and experiences. In this sense, some of the questions of the sequence are oriented to make students reflect on why they are doing each task and where each task should be leading them (i.e., to promote students' metacognition).

[4] Generally, a conceptual model is understood as an external representation of real objects, phenomena, or situations, shared by a given community (researchers, teachers, engineers, etc) and coherent with scientifically accepted knowledge, that facilitates the comprehension or the teaching of systems or states of affairs in the world and that results in a powerful explicative and predictive tool for the interaction of subjects with the world (Greca & Moreira, 2000).

Another design principle relating to the structure of the TLS was taken into account. The TLS on APM is constituted by multiple types of activities and the sequence of activities is organized taking into account the purpose of each activity and the stage of the learning cycle in which the activity is implemented. Thus, the sequence of instruction involves the following phases:

1. Engagement of students and eliciting of students' previous ideas: discussion from key questions or posed problems, justification of certain statements and/or predictions using preliminary models, etc.
2. Introduction of new concepts or procedures: observation, design and realization of experiments using MBL technology, discussion from key questions or posed problems, interpretation of experimental results and/or graphs, use of analogies, etc.
3. Structuring one's own knowledge: contrast of different perspectives, elaboration of explanations, reflection on one's own conclusions, etc.
4. Application of the developed knowledge: application of the conceptual models in different situations, use of procedural knowledge in designing and performing experiments to carry out an investigation.

Regarding classroom management, most of the aforementioned tasks were undertaken in small groups of students. A balance between assignments in small groups and whole class discussions was also promoted so that teachers and students provided feedback for formative assessment.

In short, several design principles informed the TLS on APM and oriented the pedagogical approach of the material, the teaching strategies, and the organization of the teaching and learning activities.

3.1.2 Subject matter clarification and analysis of students' learning needs

According to the Model of Educational Reconstruction (Duit et al., 2005), a good design process also requires sensitivity to students' learning needs and to reconsider (or "reconstruct") the scientific content to be taught from an educational perspective.

Taking this perspective into account, the design of the sequence on APM involved several stages addressed to critically analyse the subject matter and the educational significance of the topic for 15–16 year-old students. Thus, the design of the sequence comprised the following three phases:

- Analysis of the subject matter and its technological applications, based on several publications on the topic coming from different fields: acoustics, engineering, architecture, physics, and materials science.
- Review of previous research studies about students' conceptions of the nature and propagation of sound.
- Preliminary research study about 15–18 year-old students' conceptions on sound attenuation and acoustic properties of materials.

Analysis of the subject matter

Sound is a classic area of physics present in most science syllabuses. Linking sound with the important everyday idea of noise pollution is also common in syllabuses with an STS (Science-Technology-Society) or contextualized approach. Understanding noise pollution needs to be accompanied by a real understanding of how sound propagates and how sound is attenuated. For the design of the TLS on APM we took into account these elements (noise pollution, sound propagation and sound attenuation) but we also focused on some technological aspects (applications) in our attempt to introduce ideas of materials science. Accordingly, the designed TLS on APM is focused on analysing the relationship between properties and internal structure of specific materials in order to account for their acoustic behaviour, that is, the way materials behave in front of sound regarding attenuation. The approach to the study of sound and acoustics in combination with materials means an innovative and challenging approach in our educational context since we have no evidence of the existence of any previous didactical transposition[5] on this topic for secondary school students.

Different specialized sources, such as web sites, doctoral dissertations (Ruiz, 2005; Juliá, 2008) and books (Long, 1980; Recuero, 2000; Rossing, 2007), were used on the topic of sound attenuation and acoustic properties of materials in depth.

The consulted bibliography generally presents sound attenuation as the combined effect of scattering and absorption produced by materials, which weakens sound further than the mere propagation of sound when it spreads through a medium. The designed sequence does not distinguish between scattering and reflection of sound but emphasizes reflection as one of the mechanisms of sound attenuation when sound reaches an interface between two mediums. Absorption is understood as the energy dissipation of sound waves within a single medium. From this perspective, two types of sound attenuating materials are distinguished depending on the mechanism of sound attenuation that predominates: sound reflectors and sound absorbers.

Nevertheless, in such consulted literature sound attenuation is often not of intrinsic interest as a phenomenon. Rather, most of the sources mainly focus on the acoustic properties of materials and other variables that affect sound attenuation (e.g., frequency of the emitted sound, shape of the surface of objects and thickness of material plates, etc). Understanding the variables that affect sound attenuation is the first step to be able to control these variables when designing and selecting appropriate materials for soundproofing (avoiding sound coming from or going outside a room) and acoustic treatment (adjustment of sound reverberation).

Concerning the interaction between sound and materials, one common magnitude that is generally mentioned as related to properties of materials that affect sound transmission is the acoustic impedance (Z) of a material, defined as the product of its density (ρ) and acoustic velocity (v):

[5] The didactical transposition consists of the migration of knowledge from the community of reference, called the reference knowledge, towards the knowledge to be taught (Chevallard, 1991). In our case, the reference knowledge is the scientific knowledge whereas the knowledge to be taught can be found in the community of teachers and researchers in the form of the designed TLS.

$$Z = \rho \cdot v$$

Since acoustic velocity or speed of sound propagation through a certain material medium is generally defined as:

$$v = \sqrt{\frac{k}{\rho}}$$ (*k* being the elastic modulus)

Then, the acoustic impedance could be redefined as:

$$Z = \sqrt{\rho \cdot k}$$

This last equation summarizes the dependence of the acoustic impedance upon two essential types of properties of the material medium through which the sound wave is travelling: elastic and inertial properties. In our didactical transposition, these properties are considered as follows:

- Elastic properties are those properties related to the tendency of a material to maintain its shape and not deform whenever a force or stress is applied to it. At the microscopic level, a very elastic material is characterized by atoms and/or molecules with strong attractions among each other. When a force is applied in an attempt to deform the material, the interactions among its particles prevent the deformation and help the material maintain its shape. The designed sequence characterizes materials according to their elasticity distinguishing rigid materials (high elasticity or high elastic modulus *k*) from flexible materials (low elasticity or low elastic modulus *k*).
- Inertial properties are those properties related to the object's tendency to change its state of motion. The density of a material (ρ) is the magnitude related to the inertial property. At a microscopic level, density is related to mass of the particles that form a material and to packing of these particles. The designed sequence depicts density of solid materials as related to the inertia or mass of their particles (considering equal volumes). According to this view, the greater the inertia of the particles of a medium, the less responsive they will be to the interactions between neighbouring particles.

Acoustic impedance is therefore a magnitude that plays a relevant role in determining sound transmission and reflection at the boundary between two mediums that have different acoustic impedance. In fact, sound reflection only occurs when sound reaches the interface between two materials with different acoustic impedances. The difference in acoustic impedance is commonly referred to in specialized bibliography as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the boundary between two mediums. Rephrasing the idea of impedance mismatch in our didactical transposition, we can consider that the greater the difference between density and elasticity of two mediums, the greater the percentage of energy that will be reflected and the lesser the percentage of energy that will be transferred to the material when sound reaches the interface. Therefore, very elastic and dense materials usually behave as good sound reflectors to attenuate sound that propagates through the air. On the contrary, sound absorbers behave as bad sound reflectors, and therefore, are usually less elastic and dense.

While acoustic impedance is a magnitude useful in explaining the distribution of energy that is reflected towards the same medium or is transferred to another material when sound reaches an interface between two mediums, it does not account for how sound is absorbed within a certain material. Apart from density and elasticity, which actually affect the acoustic behaviour of materials, the effect of porosity is also recognized as a property of materials that affects sound absorption. When sound reaches a porous material, it is mainly absorbed. In our qualitative description of the phenomena, this effect can be explained in terms of the friction between the air inside the material (within the pores, between fibres) and the solid walls (or skeleton) of the material. Moreover, when sound propagates within a porous material, it is reflected many times because there are several air-solid-air interfaces. Due to friction and to the multiple reflections within the pores, part of the energy associated with sound is transferred to the solid skeleton of the material, by making its particles vibrate and therefore, it is dissipated. In summary, porous materials usually behave as good sound absorbers but bad sound reflectors.

The soundproofing of a real room or precinct, as the consulted specialized and technical literature describes, would need to take into account other factors that play a role in sound attenuation, such as the frequency of the emitted sound, the shape of the surface of an object, the thickness of the plates of material, among other things. However, the level of the students to whom the designed sequence was addressed and the complexity of the topic were considered as strong reasons to limit the sequence to the study of properties of materials that affect their acoustic behaviour. These paragraphs summarize the main ideas resulting from the didactical transposition carried out for teaching about sound attenuation (sound reflection and absorption) and about the properties and internal structure of materials that play a role in their acoustic behaviour (density, elasticity and porosity).

Review of previous research on students' conceptions of sound

Identifying the preconceptions that influence students' understanding of sound phenomena was a central step in designing the TLS on APM. Several previous studies carried out during the last two decades have focused on students' representations and common preconceptions of sound, before or after a formal instruction. The main findings of these studies could be summarized as follows:

Students' conceptions of the nature and propagation of sound

The most common result obtained from several research studies intended to analyse students' preconceptions of the nature of sound is the evidence of a mechanistic spontaneous reasoning or mental model, often named "entity model" of sound. This model can be characterized in terms of the following attributes:

- Sound signals are conceptualized as material objects created and set in motion by the source.

- Sound is considered an entity which is transported by individual molecules (*sound particles*), which move along a medium.
- Sound is considered an entity which is transferred from one molecule to the other of a medium but is different from the medium where it propagates.
- Sound is considered a limited substance which travels with a certain impetus, and is generally represented as an air current.
- Sound is considered a substance which travels following the pattern of waves.

This kind of spontaneous reasoning has been evidenced in elementary school students (Mazens & Lautrey, 2003), as well as in secondary school students (Maurines, 1993; Eshach & Schwartz, 2006) and undergraduate physics students (Linder, 1992; Hrepic, Zollman, & Rebello, 2010; Wittmann, Steinberg, & Redish, 2003).

Students' conceptions of the interaction of sound with matter

Some research studies (Linder, 1993; Maurines, 1993) also analysed students' explanations of the factors that affect the speed of sound and the interaction of sound with a certain medium. The main findings are:

- Molecules of a medium are conceptualized as an obstacle to the propagation of sound through the medium.
- The speed of sound is conceived as dependent on the source or the signal amplitude but independent of the properties of the medium.
- Even recognizing that speed of sound depends on density and elasticity of materials, density is often conceptualized as related to the distance between the molecules of a medium and elasticity is conceptualized in terms of compressibility, and as inversely proportional to density.
- Sound can propagate through the vacuum and can be transmitted through the empty spaces between the particles that form a medium.

In short, these research studies evidence that previous knowledge of students in any educational level tends to be materialistic or "based in substances". This implies that students tend to attribute properties or behaviours of material substances to abstract concepts as in the case of sound, which is ontologically conceived by the science as a process or event rather than an entity.

Preliminary research study on students' conceptions of sound attenuation and acoustic properties of materials

Although many aspects and attributes of the so-called "entity model" of sound had been described and reported by several authors, we did not find any study devoted to the analysis of students' conceptions of the specific topics we wanted to address in the TLS on APM – mechanisms of sound attenuation and acoustic properties of materials. For this reason, we decided to specifically explore 15–18 year-old students' ideas on this topic. The sample of this preliminary study (Hernández, Couso, & Pintó, 2011b) was formed by 76 upper secondary school students, who were administered a questionnaire containing a question that asked them to explain why some materials attenuate sound more than other materials. The questionnaire was administered after having performed an experiment in which students had measured sound transmitted through different materials to determine the best sound insulator. Analysing students' answers, we interpreted the properties of materials that students consider affect their acoustic behaviour and the students' understanding of the phenomenon of sound attenuation. The findings of this study can be summarized as follows:

Students' conceptions of the phenomenon of sound attenuation

About half of the students (40/76, 53%) explained some mechanisms of sound attenuation. The rest of them did not explain what they understood by sound attenuation but mentioned certain properties of materials that might affect their acoustic behaviour to explain differences of sound attenuation caused by different materials. From the answers of the students who explained some mechanism of sound attenuation, we could evidence some preconceptions:

- Most of them (15/40, 38%) considered that sound insulators behave as sound barriers that prevent the passage of sound. This kind of conceptualization might imply an underlying idea of sound as a physical entity that can or cannot go through a material depending on certain characteristics of the material, such as porosity. This conception was labelled “sound attenuation by hindering the entrance of sound”.

- Some students (5/40, 13%) conceptualize sound attenuation through a material as the decrease of the speed of sound within the material. Therefore, these students consider that the speed of sound is not constant through a uniform medium, but decreases while sound propagates through it. This conception was labelled “sound attenuation by slowing down sound”.
- Some students (6/40, 15%) also recognized sound absorption as a phenomenon that accounts for sound attenuation even though they did not give any explanation of absorption in terms of energy dissipation. In many cases, the students who explained sound attenuation as the absorption within a material evidenced a materialistic reasoning in terms of the “entity model” of sound. This conception was labelled “sound attenuation by capturing sound”.

Students’ conceptions of acoustic properties of materials

Most of the students (64/76, 84%) responded to the questionnaire mentioning different properties that might influence the acoustic behaviour of materials. The analysis of their answers evidenced to some extent that students’ conceptions of sound and sound attenuation are closely related to the properties that they associate with the acoustic behaviour of materials. Nevertheless, as stated above, some students’ conceptions of sound and sound attenuation are inconsistent with the scientific perspective and so are their conceptions of acoustic properties of materials. As an example, some students who express the idea that sound insulators are denser and non porous also conceptualize sound attenuation through a material as the obstruction of the passage of sound.

Furthermore, students’ conceptualizations of specific properties of materials at the level of their microstructure also tend to be oversimplified in some cases.

As Linder (1993) already reported, many students consider that density of materials uniquely depends on the distance between its particles.

Considering the differences between the content to be taught and the students' conceptualizations of this content, the learning demands[6] for 15–16 year-old students and for the topic addressed in the designed sequence were identified. These learning demands can be summarized as follows:

- Students' understanding of the nature and propagation of sound needs to become more coherent with the scientific view. This means conceiving sound as an event or process instead of as an entity.
- Students' preconceptions of sound attenuation need to be refined according to the scientific perspective. This refinement or change means conceiving sound attenuation as a process of energy dissipation that involves reflection and absorption rather than an effect caused by materials when "hindering the entrance of sound", "slowing down sound" or "capturing sound".
- Students' conceptualization of the acoustic properties of materials (density, elasticity, and porosity), at both macroscopic and microscopic levels, needs to become more coherent with the scientific perspective. For instance, this would imply considering density of solid materials as related to the mass of their particles instead of associating it to the distance between particles.

The identification of these learning demands was useful to formulate both the specific prerequisites and learning objectives of the TLS on APM.

3.2 The sequence of teaching and learning activities as a product of the design process

As a result of the design process, a TLS on APM was obtained. The structure of the designed sequence and the main learning targets of this sequence are summarized in Table 2.

[6] The learning demands for a particular conceptual area of science are considered as the gap between everyday and school science perspectives (Leach & Scott, 2002).

Table 2: Structure of the TLS on APM and intended learning targets

Unit	Learning targets	Activities
1 *Sound - material interaction*	The global aim is to develop a conceptual model of sound attenuation in terms of energy. This aim can be specified in terms of the following learning targets: **LT1.1** To describe sound attenuation as the decrease of sound intensity level, associating this decrease to the difference between emitted sound and transmitted sound **LT1.2** To measure the sound attenuated through obstacles using a sound level meter **LT1.3** To identify the phenomena involved in sound attenuation through materials (reflection and absorption) **LT1.4** To distinguish sound insulators according to their acoustic behaviour (sound reflectors and sound absorbers) **LT1.5** To explain and to represent (with diagrams) sound attenuation as a process of energy dissipation, identifying some mechanisms of dissipation such as friction or dispersion	**1. 1 Acoustic problems of a disco** - Exploration and discussion of the context of the sequence and the problem to be solved - Eliciting of preliminary conceptions of sound propagation through different mediums **1.2 Why can sound reach any corner of the dance floor?** - Eliciting of preliminary conceptions of sound reflection and reverberation - Exploration and interpretation of data, graphs and images to draw conclusions on sound reflection and reverberation - Application of the refined conceptions in other activities **1.3 How can we manage to avoid hearing too much sound outside the disco?** - Eliciting of preliminary conceptions of sound attenuation - Introduction of the scientific point of view regarding sound attenuation - Interpretation of the acoustic behaviour of two materials (sound reflector and sound absorber) using two diagrams that represent the distribution of energy (reflected, absorbed, transmitted) of an incident sound caused by each type of material - Design and realization of an experiment to determine, using a sound level meter, how much sound is attenuated by a certain material - Structuring of ideas in answering a question about soundproofing.
Unit	**Learning targets**	**Activities**
2 *Properties and internal structure of sound reflectors and sound absorbers*	The main aim is to develop: - A conceptual model of sound reflectors and absorbers in terms of the physical properties that affect their acoustic behaviour. - A conceptual model of sound reflectors and absorbers in terms of their internal structure. These aims can be specified in terms of the following learning targets: **LT2.1** To determine the acoustic behaviour of materials (sound reflectors and sound absorbers) measuring/analysing the levels of sound intensity **LT2.2** To predict and explain how sound is attenuated (by reflection or absorption) when it reaches a material in terms of its acoustic properties (density, rigidity, porosity)	**2.1 Which characteristics does a good sound reflector have? And a good sound absorber?** - Eliciting of preliminary ideas on the physical properties and internal structure of sound reflectors and sound absorbers - Prediction of the acoustic behaviour of several materials on the basis of their properties - Design and realization of an experiment[7] to determine if each of the previous materials behaves as a sound reflector or as a sound absorber - Classification of the tested materials in sound reflectors and sound absorbers on the basis of the empirical results - Description of the physical properties of the tested materials on the basis of their observations - Identification of the physical properties that all the tested sound reflectors have in common (and the ones that all the tested sound absorbers have in common) - Application of the conceptual model in predicting the acoustic behaviour of some materials in terms of their physical properties

[7] This experiment consists of using a sound level meter to measure the sound intensity level produced by a sound source (e.g., a buzzer) that has been placed inside a cardboard box whose walls have been covered with a certain material. The box represents the structure of a room or closed space where there is a sound source and the material that covers the walls represent the material used to soundproof that room. This measurement is compared with the reference value, measured when the box is not covered with any material. If the sound intensity level measured within the box covered with a material is higher than the reference value, then we can conclude that the material behaves as a sound reflector. If the measured value is lower than the reference value, we can conclude that the material behaves as a sound absorber. For more details about the experiment, see Hernández, Couso, & Pintó (2011a).

	LT2.3 To distinguish the acoustic properties of materials and the characteristics of objects made of these materials that might affect their acoustic behaviour **LT2.4** To represent density, rigidity and porosity of materials in terms of their microstructure **LT2.5** To predict and explain the role that certain properties play in influencing the capacity of materials of attenuating sound according to their microstructure	**2.2 How can we explain that the properties of a material affect its acoustic behaviour?** - Explanation of how sound reflectors and sound absorbers are internally configured using an analogy[8] - Interpretation of mechanisms of sound attenuation in materials according to their internal structure - Application of the conceptual model to explain why certain property of some materials affect their capacity of sound attenuation
Unit	**Learning targets**	**Activities**
3 *Acoustic treatment and soundproofing*	The aim is to apply the previous conceptual models to design and perform a more open inquiry	**3.1 Comparing materials. Which one could be used to soundproof?** - Engagement in a decision-making process to solve the original problem of the disco. The decisions, which are concerned with the selection of the most appropriate materials to soundproof and acoustically treat different areas of the disco, are to be based on evidences and models.

The designed sequence on APM is therefore intended to promote certain learning targets, such as coherent conceptual understanding of the conceptual models. Furthermore, the designed sequence is intended to contribute to students' development of inquiry skills, such as observation, measurement, classification, making inferences and predictions, problem-solving, controlling variables, interpreting data, etc. Metacognition is also one of the thinking skills that are fostered in the sequence, by means of questions specifically aimed at making students reflect on what they are learning. Nevertheless, these aims have not been formulated as learning targets in Table 2 since they are developed not only throughout this TLS but throughout the whole science course, and so they are not explicitly assessed at the end of the implementation of the designed sequence. Finally, the whole sequence also serves some social purposes, such as to make students aware of the problem of noise pollution and to emphasize the need for soundproofing of noisy places.

4. Development and refinement of the sequence

[8] The analogy is related to the mass-and-spring model of matter and it compares particles that form each medium or material with pool balls connected by means of springs. According to this analogy, density is related to the mass of the balls and rigidity is related to the elastic constant of the springs connecting the balls. Porosity is related to the presence of air particles inside the pores of a material, which in turn is formed by different particles.

The design of the first version of the sequence was completed after having decided the students' learning targets, the activities and the procedures to evaluate the sequence. At this point, we tackled the issue of what indicators are more relevant to appraise the quality, success or impact of the innovation. As van den Akker (1999, p. 10) says, "quality is an abstract concept that requires specification". During a design process, the emphasis in criteria for quality usually shifts from validity, to practicality (or usability), to effectiveness (or efficacy).[9]

After a first implementation of the designed sequence in different schools, the members of the LWG proceeded to evaluate the quality of the designed sequence taking into account the coherence between the designed sequence and the design principles, the teachers' perceptions of the implementation of the sequence and the students' performance during the implementation of the sequence. This chapter reports the evaluation of the quality of the sequence, conducting an in-depth analysis of the role of each designed activity, at a fine granularity level (Tiberghien, Vince, & Gaidioz, 2009).

The evaluation of the validity, practicality and efficacy of the sequence resulted in a refinement of the sequence. As a result of this stage of development of the sequence, a second version was obtained and implemented in the classroom. After this second classroom implementation, teachers and researchers evaluated the redesigned sequence on the basis of the new evidence obtained. The third version of the sequence, resulting from this second evaluation, was developed and implemented again in different classrooms. The whole process is illustrated in Figure 1.

[9] Validity refers to the extent that the design of the intervention is based on state-of-the-art knowledge (content validity) and that various components of the intervention are consistently linked to each other (construct validity) and can adequately be evaluated through expert appraisal. Practicality refers to the extent that users (and other experts) consider the intervention as appealing and usable in "normal" conditions. Effectiveness refers to the extent that the experiences and outcomes from the intervention are consistent with the intended objectives.

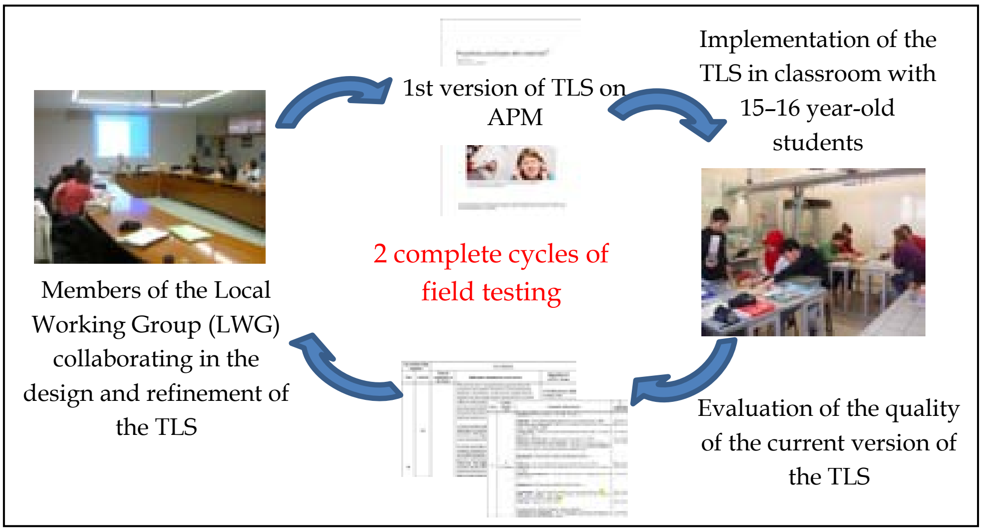


Fig. 1: Iterative development of the TLS on APM carried out by our LWG

5. Implementation(s) of the sequence

The teachers who participated in the design of the TLS also committed themselves to implement the sequence in their science classes. Some of the teachers who participated in the first classroom implementation trial of the sequence also implemented the second and third versions of the sequence. Moreover, other teachers who did not participate in the design process but were colleagues of some of the previous teachers also joined the LWG and implemented the second and third versions of the sequence in their science lessons.

The teachers involved in the LWG implemented the sequence within the course of their own science classes and with their students. In other words, the conditions under which the sequence was implemented correspond to the ordinary context of their classrooms. Some noticeable differences in practice are: (i) the teachers involved in the implementation of the sequence had different teaching styles and managed students' autonomy and collaborative tasks differently: some teachers were used to teaching by asking questions while others were more used to teaching by telling; (ii) not all the teachers implemented the whole sequence, and therefore they devoted different numbers of hours to the implementation; and (iii) teachers could not implement the sequence at exactly the same academic level but at closer ones (9^{th} to 11^{th} grade).

For these reasons, and for the purposes of the research presented here, we reduced the sample to the class groups formed by 15–16 year-old students, who are the target of the designed sequence. Moreover, all the teachers who could implement the sequence at this level have some main features in common: (i) they implemented almost the whole sequence, devoting a similar number of hours (12–15 hours) and following the written teaching and learning material as it was structured; (ii) they all proposed collaborative work and active discussion among their students to a greater or lesser extent; and (iii) they implemented at least two different versions of the sequence. Table 3 presents a general description of each of the schools to which these class groups belong as well as the number of students who constitute our sample:

Table 3: General description of sample

School	Description of the school	Number of students		
		First classroom trial	Second classroom trial	Third classroom trial
A	- Unique state secondary school in a small town between bigger cities - Mixture of socioeconomic background of students - Low number of immigrant students	22	14	-
B	- State secondary school in an urban area - Medium - High socioeconomic background of students - Low number of immigrant students	14	-	12
C	- Privately run school funded by the state in a small town - Medium - High socioeconomic background of students - Low number of immigrant students	29	16	17
A+B+C	TOTAL SAMPLE	65	30	29

6. Research questions and methods

6.1 Research questions / aims

We do not aim only at designing and validating a particular innovation on a certain topic or at improving gradually the quality of the designed sequence refining it. Rather, the main aim of this research is to analyse different aspects of the process of iterative development of the innovative TLS on APM, in an attempt to make explicit some of the features of a process of iterative development of an innovation in science education. This essential aim is addressed by the following research questions:

1. *What problematic aspects of the innovative TLS are identified when evaluating and analysing it after having been implemented in real classroom contexts with 15–16 year-old students?*
2. *What changes are introduced in the designed TLS aimed at overcoming the identified problematic aspects?*
3. *What "driving forces" or "critical reasons" are associated with the changes introduced in the designed TLS?*

6.2 Research methodology

This study has used an interpretive qualitative approach to examine the basic structure of the event under study – the process of iterative development of a TLS on APM – and to generate a model of successful innovation through such work.

As the present study is framed within the design-based research paradigm, we used a range of mixed methods and techniques to analyse the intervention's outcomes and refine the sequence: observation, collection of standard learning tasks with scoring rubrics, and other techniques for learning assessment. Assessment techniques are domain specific, that is, specific to the content being taught and the goals, and so new instruments have been developed for collecting data in the domain of APM, covered by the designed TLS.

6.3 Data collection

In order to analyse the process of iterative development of the designed sequence, we collected several data (Table 4) during and after the three classroom implementations carried out in consecutive school years. Nevertheless, the analysis of students' outcomes from the students' written answers in a common exam is not reported in this chapter (it will be published elsewhere).

Table 4: Collected data

SOURCES OF DATA	Year 2007-08	Year 2008-09	Year 2009-10
a) Students' written answers in a common exam	✓	✓	✓
b) Students' written answers and productions in their booklets	✓	✓	✓
c) Teachers' diaries describing their perceptions of the implementation process	✓	✓	×
d) Researchers' field notes after classroom observation during the implementation of the sequence	✓	✓	✓
e) External experts' reports after classroom observation during some sessions during the implementation of the sequence	✓	×	×
f) Informal notes taken during the face-to-face meetings of the LWG devoted to refining the sequence (teachers' perceptions and difficulties perceived during the classroom implementation of the sequence)	✓	✓	×

6.4 Data analysis

The first level of analysis of the collected data consisted of the identification of the students' needs or difficulties for each activity during the implementation of the sequence in order to infer problematic aspects of the sequence that had resulted in those students' needs or difficulties. After having identified problematic aspects of the sequence, a series of modifications were introduced in the designed TLS. The changes in the sequence were described in detail as well as the critical reasons or driving forces that promoted that change. Table 5 shows the instrument used to summarize the analysis of each assignment of the sequence.

Table 5: Instrument to summarize and thus evaluate each assignment of the designed sequence

# version of the sequence (# implementation)		**# evaluation**			
Assignment / Task (Booklet)	**Aim of the task**	**Students' or Teachers' needs or difficulties identified in each task**	**Problematic aspects of the sequence for each task**	**Changes introduced in the task**	**Driving forces**
Assignment #	…	…	…	…	…

As a second level of analysis, we proceeded to cross the results of the analysis of each assignment of the sequence in order to categorize the types of students' needs or difficulties, the types of problematic aspects of the sequence, the types of modifications introduced in the sequence and the driving forces associated with these changes. Once these categories were defined, we analysed the relationships between the types of students' needs or difficulties and the types of changes introduced in the sequence in order to identify possible patterns of modification that would allow us to describe aspects of the refinement of the sequence.

Finally, as a third level of analysis, we evaluated the quality of the refinement of the sequence by comparing types and prevalence of students' difficulties throughout the consecutive versions of the sequence. This analysis consisted of the quantification of each type of difficulty evidenced and each type of change introduced after each implementation. The resulting quantities are not related to the total number of students who participated in each implementation. On the contrary, the quantities refer to the number of difficulties (or changes introduced in the sequence) of each type that were evidenced throughout the whole sequence (without considering the same difficulty more than once). This quantification allowed a graphical representation of the evolution of the persistence of certain students' difficulties from the implementation of one version to the next.

7. Results

7.1 On students' needs or difficulties

7.1.1 Types of students' needs or difficulties

The fine-grained analysis of the collected data allowed us to evidence 15–16 year-old students' needs and difficulties when implementing the consecutive versions of the designed TLS on APM. Table 6 summarizes the types of students' difficulties identified when analysing the data collected during the classroom implementation of the first, second and third versions of the sequence.

Table 6: Types of students' needs or difficulties identified during the implementation of the sequence

Category	Description
D**M**	**Related to Metacognition**: Students do not identify the intended aim of a question / statement or do not challenge some of their own existing ideas although they are told to reflect on them critically
D**I**	**Related to Images**: Students do not interpret appropriately the meaning of a visual representation, picture or graph related to a concept or phenomenon
DC	**Related to Concepts or Conceptual Models**: Students do not use appropriately a conceptual model or do not attribute an appropriate meaning to a certain concept when predicting, interpreting or explaining phenomena
D**E**	**Related to Experiments**: Students do not control the variables, do not evaluate the limitations of an experiment when designing and planning it, do not interpret appropriately the magnitude or values of the measurements they take with an instrument or do not analyse adequately the experimental data they collect
D**O**	**Related to Other Aspects**: Students are not familiar with the procedures of a certain kind of assignment or do not give a written answer in their booklets

Student's needs or difficulties related to metacognition

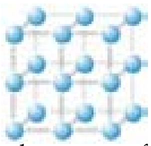
The students' difficulties related to metacognition (DM) refer to the familiar problem that several authors have previously reported as "*the problem of students not knowing the purpose(s) of what they are doing, even when they have been told*" (Gunstone, 1992). The following answer from a student who participated in the implementation of the first version (V1) of the sequence is intended to exemplify this type of difficulty:

> After having measured the variation of the intensity level of a constant sound source as the distance between the source and the sensor (sound level meter) increases, students were asked:
>
> **Question** (**V1**): From the measurements obtained in the previous tests, which conclusions can you reach?
>
> **Student's answer**: "*Our predictions [graphs] are quite similar to the real ones, but they would be more similar if there was not so much noise in the classroom*" (S01B)

The previous quote highlights that the student does not explain or interpret the experimental results in terms of the decrease of sound intensity level as the distance between the source and the sensor increases, as expected, but s/he slightly compares his/her own prediction with the obtained graph. Although the previous example of activity is not a metacognitive task since it does not ask students to make an explicit statement about the purpose of the question, we interpret that this answer plausibly evidences a lack of the student's awareness of the aim of the activity and thus, we consider that the student's difficulty in this answer is related to metacognition. Other students' difficulties related to metacognition were evidenced in answers to metacognitive tasks, in which students were explicitly asked to reflect on their previous ideas, to compare them with different ones and to refine them.

Student's needs or difficulties related to images

Students having difficulties reading images (DI) is another common problem identified during the implementation of the sequence. Students' difficulties reading visual representations are in some cases associated with students' (lack of) understanding of the concepts represented in the image but often they are also attributed to problematic features of the designed images and their accompanying verbal elements. The images that are part of the TLS were designed and introduced as a visual aid for students' understanding of processes or concepts. In this sense, the TLS is considered the *interpretative context* (Ametller & Pintó, 2002) where images convey a certain meaning. Nevertheless, in some cases such interpretative context seems not to be enough or adequate since we evidenced that some students did not interpret appropriately the meaning of the image (and its caption) or simply did not make any sense of it. Let the next quote serve as an example of this type of difficulty:



Model that relates the internal structure of a material and its rigidity
(Molecules are represented by balls and bonds are represented by springs)

The ball-and-spring model and its corresponding caption were included with the purpose of contributing to the building of a conceptual model that relates the rigidity of materials to the strength of the bonds between its molecules. After having introduced the image and caption shown above, students were asked the following question:

Question (V1): Using the microscopic model of a material, explain how rigidity of a material affects the fact that the material reflects sound.

Student's answer: "*If a material is more rigid, the atoms are less prone to move and transmit sound because the springs are less deformable and the atoms vibrate less*" (S07B)

As the previous example illustrates, this student explains rigidity of a material at the level of its internal structure in terms of "springs" between atoms as represented in the image. Although the previous student's answer can be interpreted as a good explanation of sound transmission/attenuation in a material in terms of the vibration of its particles, we consider this answer problematic since it mixes elements from the source of the analogy (springs of the image and their property of "deformability") with elements from the target of the analogy described in the caption (atoms). Bonds don't appear in the answer but are substituted by springs. Thus, we interpret that the student's difficulty is related to the image used with the analogy. We consider that if the student had been able to integrate the information provided by the caption with the visual elements of the image, s/he might have been able to "decode" the analogy.

Other problems identified regarding images are concerned with the inadequate interpretation of graphs or of a collection of static images which represent a process or phenomenon.

Student's needs or difficulties related to concepts or conceptual models

The third type of students' difficulties evidenced in analysing students' answers corresponds to the conceptual difficulties (DC). Let us note that for this analysis we did not consider students' difficulties evidenced in eliciting their previous ideas, although some of these ideas might be inadequate. That is to say what we report here as conceptual difficulties are those students' problematic conceptions or reasoning evidenced after students' involvement in tasks and assignments that were devoted to promote students' understanding of a certain concept or conceptual model. Therefore, we only considered as students' difficulties those students' conceptions, different or similar to students' previous ideas, which are not consistent with the scientific perspective and have not been overcome throughout the sequence. Thus, these students' difficulties allow interpreting the weak points of the designed sequence. The following student's answer evidences some conceptual difficulties:

After having observed several porous materials (with the naked eye and with a binocular microscope), having been introduced to a verbal description of the internal structure of porous materials and having had explained sound attenuation in terms of energy, students were asked the following question:

Question (**V1**): Using the microscopic model of a porous material, explain how porosity of a material affects the fact that the material absorbs sound.

Student's answer: "*If a material is very porous, its atoms are more separated and therefore, sound can rest within the spaces between atoms where there is air*" (S17C)

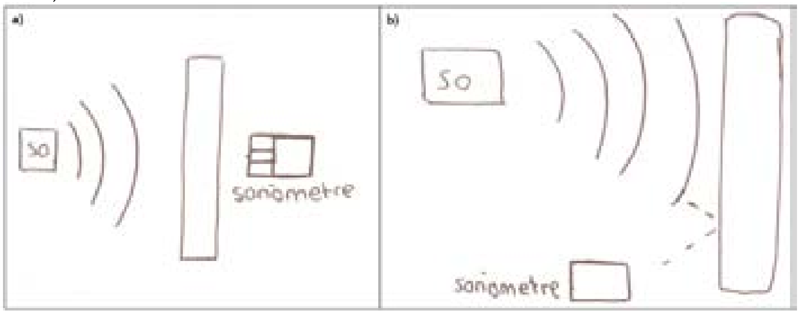
The previous answer evidences that the student thinks of porosity as a property of the material related to the distance between atoms. The fact that this student considers that "there is air between atoms" suggests a weak understanding of the particulate model of matter. Moreover, the student expresses that "sound can rest within the spaces between atoms". We interpret that the student conceives sound as an entity that can penetrate the material and remain there (Hrepic et al., 2010).

The lack of justifications of statements and predictions in terms of a certain conceptual model, as well as the use of certain terminology with an inaccurate meaning (e.g., reverberation as synonymous with echo, material as synonymous with object, elastic as synonymous with flexible), were also considered as students' conceptual difficulties.

Student's needs or difficulties related to experiments

Concerning the experimental tasks (DE), we could evidence some students' difficulties associated with certain practices, such as control of variables, design of experiments, analysis of empirical data, etc. As an example, the following drawing corresponds to the design of an experimental setup, drawn by a student in his booklet.

Question (**V1**): Draw a diagram of the experiment that you would carry out to test whether a material is:
a) A good sound insulator
b) A sound reflector



Student's drawing (S16A)

The previous drawing evidences that the design proposed by the student does not take into account that sound attenuation should be measured outside a closed space to avoid measuring the intensity level that corresponds to direct sound. The drawing does not indicate either that it is necessary to measure a reference value against which one can compare other measurements of sound intensity level in order to test if a certain material attenuates sound a lot or a little or reflects sound more or less than other materials.

7.1.2 Student's needs or difficulties identified throughout the implementations of consecutive versions of the sequence

After having identified and categorized the types of students' needs and difficulties for each task of the sequence, we analysed the prevalence of each type of difficulty during the implementation of the first, second and third versions of the sequence. Figure 2 presents a histogram showing the number and type of students' difficulties identified after the implementation of the first, second and third versions of the sequence. Thus, this graphical representation shows the evolution of students' difficulties as a result of the evaluation and refinement that was carried out from the first (V1) to the second version (V2) of the sequence and from the second (V2) to the third version (V3) of the sequence.

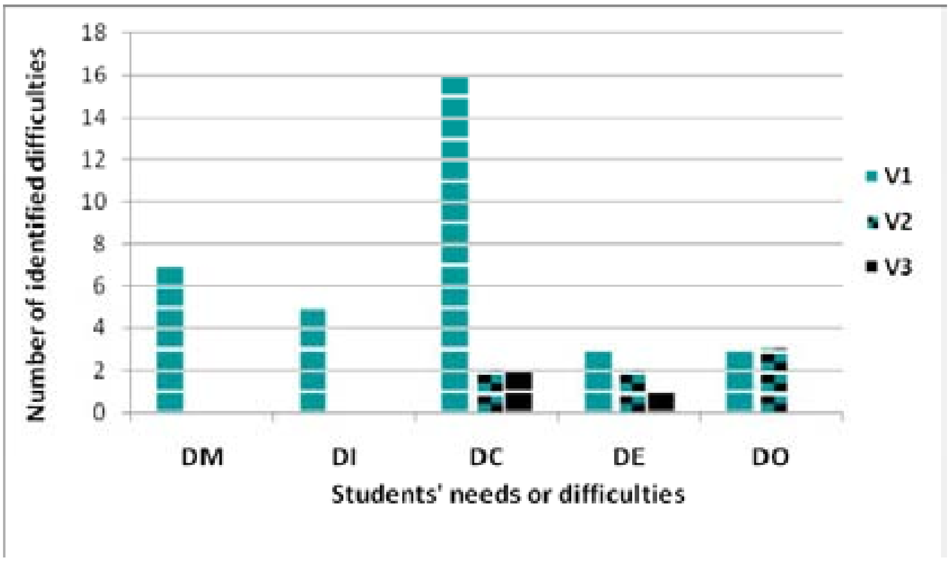


Fig. 2: Prevalence of students' needs or difficulties when implementing three consecutive versions of the sequence

As shown in Figure 2, the type of difficulty most commonly evidenced in the first version of the sequence is related to the use of concepts and conceptual models (DC). The histogram also shows that in the second version of the sequence, fewer difficulties were evidenced and the difficulties related to concepts were not the most frequent type of difficulty. Other sorts of difficulties (DO), such as students' lack of familiarity with the procedures of a certain kind of task (e.g., concept maps), was the most frequently evidenced during the implementation of the second version. The tendency towards a decrease in students' difficulties is also evident after the implementation of the third version of the sequence.

7.2 On the problematic aspects of the sequence and the modifications introduced

The analysis of the quality of the sequence also led us to interpret the problematic aspects of the sequence that might have resulted in certain teachers' and students' difficulties. Table 7 summarizes the types of changes that were introduced in the two first versions of the sequence (to obtain V2 and V3 of the sequence respectively) when refining them according to the problematic aspects (in bold) of the sequence that were identified.

Table 7: Types of changes introduced in the sequence when refining it

Code	Description
CQ	Reformulation of **questions / statements** of the sequence
CI	Re-elaboration of **diagrams, graphs and images** or introduction of additional **visual representations and their meaning**
CC	Introduction of additional **concepts** and **analogies or** adaptation of the **terminology**
CA	Addition or deletion of certain **activities**, re-elaboration of the **approach** of certain **activities** or modifications to the **structure of the designed sequence** (order of the activities)
CG	Addition of **guidelines / specifications** about how to do a task
CF	Modifications to **editing format**

7.2.1 Types of modifications introduced in consecutive versions of the sequence

The prevalence of each type of change introduced in the sequence after each cycle of refinement was also analysed and represented graphically (Figure 3).

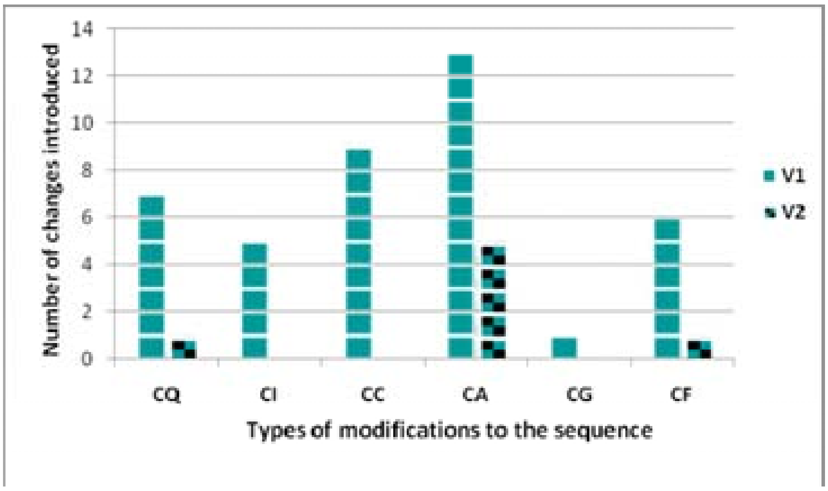


Fig. 3: Prevalence of types of modifications introduced in the sequence when refining consecutive versions of the sequence

As shown in Figure 3, the most frequent types of change introduced in the first and second versions of the sequence are related to the addition, deletion or modification of certain activities re-elaborating their approach (CA). The histogram also shows that fewer modifications were introduced in the second version of the sequence in comparison with the first version.

7.2.2 Relationship between students' needs or difficulties and changes introduced in the sequence

Beyond the analysis of the number and types of changes introduced in the sequence when redesigning it, we focused on the possible relationships between these changes and students' needs or difficulties. The different changes were purposely introduced in the sequence in order to overcome the different types of students' difficulties previously identified. That is to say, each type of students' need or difficulty was addressed by a specific type of change in the sequence. The changes introduced in the sequence to deal with each type of students' difficulty are described below.

Changes introduced in the sequence to tackle students' needs or difficulties related to metacognition

With the intention to overcome students' difficulties related to metacognitive aspects (DM), two types of changes were mainly introduced in the sequence: modifications to the questions or statements (CQ) and modifications to the activities (CA). The following example is intended to illustrate a change of wording introduced in the statement (CQ) of one of the activities of the sequence and the effect of these changes in students' answers:

	→	
Question (V1): From the measurements obtained in the previous tests, what conclusions can you reach? **Student's answer**: "*Our predictions [graphs] are quite similar to the real ones, but they would be more similar if there was not so much noise in the classroom*" (S01B)	→	**Question (V2)**: From the graph you obtained, explain how the distance between the sound level meter and the buzzer affects the measurements of sound intensity level. **Student's answer**: "*The further [the sound level meter] is [from the buzzer], the less sound it can detect*" (S04A)

The answer of the students to the question, as formulated in the first version of the sequence, exemplify that the modifications to the wording of a statement (CQ) in students' booklets results in students' identification of the aim of the question.

The next pair of statements corresponds to another task of the sequence that underwent changes in its approach (CA). That is to say, the activity was modified so that it keeps the same aim but the demand to students is adapted.

	→	
Question (V1): In the previous activities you developed an explanation about the influence of density, rigidity and porosity on the reflection or absorption of sound produced by materials. Now you can read how science explains the same relationships. [Comparing your explanation and the one elaborated by scientists] What should you improve in your model?	→	**Question (V2)**: You have just read a scientific explanation that accounts for how density, rigidity and porosity of materials affect the fact that these materials behave as good sound absorbers. Based on the previous explanation, explain how sound reflectors attenuate sound and how their physical properties make them behave as good sound reflectors.

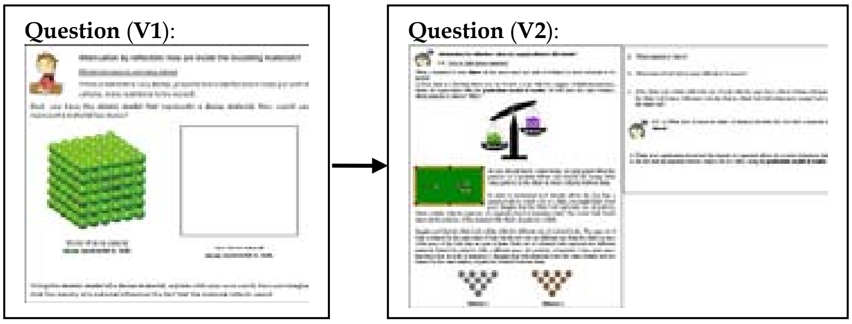
In this task students were expected to reflect on how they explained sound attenuation in materials in terms of their properties and internal structure after having read and discussed a scientific explanation. About 70% of the students did not answer the previous question in the first version of the sequence. We interpret that either these students might not be familiar with activities that involve comparison of explanatory models, reflection on and refinement of one's own models, or they did not receive enough support to carry out the task, as formulated in V1. In any case, we decided to modify the approach (CA) of this activity in order to adjust the scaffolding provided to students in their necessary evolution of their preliminary models towards the intended conceptual models. The analysis of students' answers to the modified question (in V2 of the sequence) evidenced that about 90% of the students accounted for the acoustic behaviour of sound reflectors in terms of their internal structure and describing some mechanisms of sound attenuation.

Changes introduced in the sequence to tackle students' needs or difficulties related to images

The students' difficulties related to the interpretation of the meaning of images (DI) were mainly tackled re-elaborating diagrams, graphs and images or introducing additional visual representations and their meaning (CI). For instance, in the first version of the sequence students were asked to interpret different images that represented phenomena (e.g., sound reflection and sound diffraction) by means of "sound rays" and wavefronts. The students attributed different meanings to both representations, considering in some cases that they are contradictory since students conceive that wavefronts represent sound propagating spherically in multiple directions but sound rays represent sound propagating in one direction. In the second version of the sequence, the meaning of these representations was explicitly introduced in an introductory chapter, explaining that sound rays in our didactical transposition indicate the direction of propagation of sound in which most of the energy is transmitted.

Changes introduced in the sequence to tackle students' needs or difficulties related to concepts or conceptual models

With the intention to overcome students' conceptual difficulties (DC) and to further scaffold the process of students' building of certain conceptual models, two main types of changes were introduced: introduction of the scientific meaning of certain concepts (CC), distinguishing it from the meaning attributed to them in everyday life, and modification to the approach of some activities (CA). We describe below the evolution of one of the activities from the first to the second version of the sequence, as an example of modification to the approach of an activity of the sequence to overcome certain identified conceptual difficulties of students.



The activity shown in the picture above asked students to represent the density of a material at the level of its microstructure in terms of the particulate model of matter. Moreover, they were asked to explain how density affects the acoustic behaviour of materials in terms of their internal structure. In the first version of the sequence, the drawings made in this activity evidenced that about half of the students conceptualize density as being related to the distance between particles. Nevertheless, this conceptualization of density seems to be related to the attribution of corpuscular properties to sound (e.g., *"If a material is very dense, sound waves do not have space to enter or trespass because all the particles are very close to each other"* – S02A).

In order to support students' use of the particulate model of matter when conceptualizing density at the level of the internal structure of materials, some questions and an analogy (described in Table 2) were added in this activity. In the second version of the sequence, density is then conveyed as a property related to the molecular weight (and to inertia of particles). The questions introduced are intended to guide students' reasoning about the mechanisms of sound attenuation in terms of collisions between particles and resistance of particles to vibrate, with the purpose of overcoming the conceptualization of sound attenuation as the process of "hindering the entrance of sound". In definition, the purpose of this activity did not change from one version to the next version but the approach of the activity did.

Changes introduced in the sequence to tackle students' needs or difficulties related to experiments

Concerning the students' difficulties evidenced in experimental tasks (DE), various types of changes were introduced in the sequence to deal with those difficulties: adaptation of the approach of the tasks (CA), introduction of specific concepts (CC) and further guidance or specifications on the procedures of the task (CG). The activity described below is an example of an experimental task whose approach has been modified with the intention of supporting students in the design of an experiment intended to determine if a material behaves as a sound reflector or as a sound absorber.

Question (**V1**): How can we test empirically whether a material is a sound absorber or sound reflector?

a) Prepare a list of materials and objects that you think you would need in order to do the experiment.

b) Draw a diagram or sketch of the experiment that you would carry out in order to test if a material is a good sound reflector.

→

Question (**V2**): How can we test empirically whether a material is a sound absorber or sound reflector?

a) How would you test whether the materials used to cover the ceiling and the walls of a disco are sound reflectors or absorbers?

b) Draw a diagram of the experiment you would carry out in the classroom or in the laboratory in order to test if a material is a sound reflector or a sound absorber.

The previous activity was modified after having evidenced that students had difficulty devising experimental designs that can be prepared in a laboratory to solve real problems. In the first version of the sequence, students were posed the problem of a disco's owner who wanted to distinguish sound reflectors from sound absorbers to make an adequate choice of materials to treat the disco acoustically. After this contextualization of the activity, students were asked to design an experiment to distinguish sound absorbers from sound reflectors in the lab. In the implementation of the first version of the sequence, more than half the students (55%, 36/65) proposed an inadequate experimental design to test whether a material behaves as a sound reflector or as a sound absorber. In the second version of the sequence, the approach of this task was modified so that students were first asked to devise a possible experimental design that real technicians could perform in the real context and then they were asked to adapt their design to the resources available in their school labs. This intermediate step turned out to be useful since in the second version of the sequence about 85% of students described an appropriate and feasible experiment to test the acoustic behaviour of a certain material in the laboratory.

Changes introduced in the sequence to tackle other needs or difficulties of students

Finally, other difficulties (DO) identified in the implementation of the sequence, which are related to students' lack of familiarity with the procedures of a certain task or lack of written answers, have been tackled by changing the approach of the activity (CA) to make it more familiar to students, or adapting the format of the activities (CF) when editing the students' booklet.

7.3 On the "driving forces" or critical reasons for change

To complement the description of the circumstances and agents involved in the process of iterative development of the TLS on APM, we consider it essential to report the critical reasons that have driven us to refine the sequence in the way we have done. These critical reasons or "driving forces" are summarized in Table 8.

Table 8: Critical reasons or "driving forces" to refine the sequence

Code	Description
DF1	Need for further readjustment / adaptation of the activities of the sequence to the intended "Design Principles" for improving validity
DF2	Need for tackling teachers' needs or difficulties in order to enhance the practicality of the designed sequence
DF3	Need for tackling students' needs or difficulties to enhance the efficacy of the designed sequence

Reflecting on the reasons that we argued for each of the changes introduced in the sequence, we establish some links between these reasons and the criteria to evaluate the quality of an innovation (van den Akker, 1999).

Enhancing the validity of the designed sequence by readapting the activities to the design principles (DF1)

According to Nieveen (2009), an innovation such as the TLS on APM is considered valid if it is based on state-of-the-art knowledge and if it is "logically" (or consistently) designed. Although it is clear that the design of the sequence was mainly based on theoretical assumptions and previous research results, its consistency needed to be appraised by comparing the intended design principles and the learning activities actually designed. This critical analysis was carried out resulting in the introduction of modifications to the sequence or in making explicit certain design principles that were used for the redesign. For instance, all the modifications to the organization of the activities[10] have been introduced after reflecting on the intended content structure of the sequence in order to group or reorganize the activities that deal with the same concept or phenomenon. Another type of modification influenced by this factor is the adaptation of the guidance provided to students in some activities to support their modelling processes or development of certain skills. Some of these changes were based on certain needs of students that had been evidenced but they were also argued in terms of the intended design principles, which explicitly highlight the need for providing gradual scaffolding and a variety of activities with different purposes throughout the sequence to support students in their learning process.

As a result of this critical analysis, we were able to readjust the designed TLS to the intended design principles and thus, to enhance the validity of the designed sequence.

Enhancing the practicality of the designed sequence by tackling teachers' needs or difficulties (DF2)

An innovation is said to be practical if it is realistically usable in the settings for which it has been designed and developed. Thus, only the users (teachers and students) of the designed sequence can evaluate if it is easy for them to use it in a way that is largely compatible with the developers' intentions. The fact

[10] The evolution of the structure of the sequence throughout the consecutive refinements of the sequence is represented in the Appendix.

that most of the teachers who implemented the sequence also participated in its design might undoubtedly have a positive effect on their perception of the practicality of the material. Nevertheless, the classroom observations and the discussions during the meetings of the LWG also evidenced some teachers' difficulties understanding the purpose of certain activities, and thus providing guidelines to students for a certain task. Apart from discussing these difficulties among all the members of the LWG, the problematic activities which were identified were also adapted to facilitate teachers' understanding of these activities. This refinement contributed to enhancing the practicality of the designed sequence, as appraised by designer and non-designer teachers.

Enhancing the efficacy of the designed sequence by tackling students' needs or difficulties (DF3)

An innovation is considered effective if it results in the desired outcomes. For this reason, the evaluation of the efficacy of the sequence was based on the analysis of the extent to which the experiences and outcomes of the intervention were consistent with the intended objectives. As reported before, an analysis of students' needs or difficulties was carried out and resulted in modifications to different aspects of the sequence intended to overcome those students' difficulties and to enhance students' learning outcomes in future implementations. Nevertheless, this chapter reports the analysis of students' outcomes during the implementation of the sequence but not at the end. Although the details of the analysis of students' learning outcomes at the end of the sequence will be reported elsewhere, this analysis evidenced a similar tendency towards higher achievement of students' learning outcomes throughout several refinements of the sequence. In short, the efficacy of the designed sequence, which was based on the results of the systematic analysis of students' outcomes during the implementation, was evaluated and improved throughout several cycles of refinement.

Finally, having argued the reasons for each change, we analysed the weight of each reason over the total number of changes introduced throughout each iteration. Two main reasons or driving forces for the introduction of changes in the designed sequence were identified: (i) overcoming students' needs or difficulties (DF3), i.e., enhancing the efficacy of the sequence, and (ii) realigning the activities to the intended design principles (DF1), i.e., enhancing the validity of the sequence. Fewer modifications of the activities were considered necessary to support teachers' needs (DF2), i.e., to enhance the practicality of the sequence.

8. Discussion and conclusions

The analysis of the broad range of collected data, after two cycles of field testing, allowed evaluation of the quality of consecutive versions of the TLS on APM and identifying the main aspects and processes involved in the iterative refinement of the sequence.

First of all, the data collected during the implementation of the sequence were analysed with the aim of identifying difficulties which had arisen during classroom implementation of consecutive versions of the sequence. *Two main types of students' difficulties were identified: those which evidence a lack of students' progress towards the achievement of certain intended learning targets* (e.g., difficulties related to concepts or conceptual models or difficulties related to experiments), *and those which indicate an unexpected or problematic realization of a certain task* and thus, a possible factor that would hinder the achievement of certain intended learning targets (e.g., difficulties related to metacognition). As an example, the designed sequence contains certain activities that are intended to promote students' development of metacognitive skills, since they are considered relevant in themselves and moreover, they contribute to promote students' achievement of intended learning targets. Although development of metacognition is not one of the learning targets addressed by the designed sequence, students' difficulties related to metacognition have also been taken into account to identify problematic aspects of the sequence and to refine the activities consequently. A remarkable result of the analysis of students' difficulties throughout the whole process of iterative refinement is related to the overcoming of most of these difficulties. *The decrease of students' difficulties derived from the refinement of the first version of the sequence is significantly higher than the decrease resulting from the refinement of the second version of the sequence.*

The identification of students' difficulties allowed the interpretation of several problematic aspects of the sequence in each cycle of development, which is the focus of the first research question of this study. The results of this research show that *the main aspects of the sequence that were interpreted as problematic* in the first iteration were *the approach and the organization of some activities*. *The concepts and analogies selected, the terminology used and the questions formulated in the sequence* were also interpreted as problematic aspects that had a strong weight in the refinement of the first version of the sequence. Comparing the first and the second cycles of field-testing of the sequence, we evidenced that fewer problematic aspects were identified in the second iteration, which indicates that the refinement carried out was rather effective. Furthermore, other patterns were noticed in the second iteration: (i) *Not only were fewer activities considered problematic regarding their approach but also their organization was already considered appropriate*, and (ii) *The selection of concepts, analogies, terminology and images and the guidelines provided to students about how to perform certain activities were interpreted as adequate based on the evidence obtained from the previous analysis of students' difficulties.*

The second research question refers to the changes introduced in the sequence according to the problematic aspects that they address. The modifications were intended to deal with each type of difficulty identified after the implementation of each version of the sequence, such as students' difficulties related to experimental tasks or related to images. However, the identification of students' difficulties was not the only reason argued to introduce changes in the sequence. This result gives cause to discuss the third research question which deals with driving forces or critical reasons for changing different aspects of the sequence. Not only the analysis of data related to students but also the analysis of data related to teachers and the meta-analysis of the design principles of the sequence brought several reasons to argue certain modifications to the designed sequence. These driving forces have been related to the criteria followed to evaluate the quality of an innovation, as described by Nieveen (2009), since after all, the reasons for change are intended to enhance the quality of the designed sequence.

In this sense, the improvement of the efficacy of the sequence along the process of iterative refinement has been described in terms of the evolution in number and types of students' difficulties and problematic aspects of the sequence. *The decrease in the number of identified difficulties for students evidences that the iterative development of the sequence has contributed to improve the efficacy of the sequence, from the point of view of students' performance.*

On the other hand, the enhancement of the validity of the sequence was carried out by consistently readapting the designed sequence to the design principles intended for the sequence. The weight that this "driving force" had on the process of refinement of the sequence highlights the *importance of making explicit and taking into account the theoretical assumptions and design principles of the designer group in order to enhance the quality of the sequence.* According to Ruthven et al. (2009, p.329), "although iterative refinement of a design through analysis of its implementation is undoubtedly important, the cogency and efficiency with which such revision can be achieved is influenced by the quality of the original design and by the clarity and coherence of the intentions it expresses".

Finally, the quality of the designed sequence was also evaluated from the point of view of its practicality (or usability), in terms of the needs of the secondary school teachers who were part of the LWG. Unlike validity and efficacy, the evaluation of the practicality of the first version of the sequence gave rise to fewer changes and moreover, no changes were introduced in the refinement of the second iteration in relation to teachers' needs. *At the end of the whole process of iterative refinement, teachers' perception of the practicality of the designed sequence and its innovative pedagogical approach was positive.*

An accurate interpretation of the improvement in students' performance must take into account that a successful innovation is a joint product of the designed intervention and the context (DBR Collective, 2003). All the changes were agreed among the members of the LWG based on the evidence that had been obtained so that these modifications were decided with or positively received by the teachers who participated in the design and classroom implementation of the sequence. The decrease of teachers' needs or difficulties from the first implementation of the sequence to the second can be interpreted as a result of the internalization of goals on the part of teachers and their gradual familiarization with the innovative pedagogical approach and with the materials. Therefore, *the improvements in students' performance can be attributed not only to the iterative development of the designed sequence but also to teachers' increasing expertise and familiarization with the innovative sequence*.

In summary, the process of iterative development of the TLS on APM has been productive not only for supporting teachers when designing and implementing an innovative sequence and for enhancing the quality of the designed sequence, but also for the knowledge on how to refine didactical innovations that this long process of research generates.

The "tracking" of students' realization in classroom tasks, the interpretation of students' and teachers' difficulties and needs, the elicitation of and alignment with the design principles and the identification of weak and problematic aspects of the sequence has turned out to be a useful and rich analysis to inform the process of refinement of the designed sequence towards improving its quality.

9. Recommendations

Although there is a great consensus about the importance of cyclical or iterative development of teaching and learning innovations in the field of research in science education, the recognition of the educational value of this process is not so extensive among the community of science educators and curriculum developers. As McDermott (2001, p. 1128) already stated, "instructors frequently judge the success of a new course or innovation by their impression of how much the students have learned or how satisfied they appear to be". This does not seem to be a valid indicator or criterion for evaluating the effectiveness of the instruction. At least, these perceptions are not reliable in guaranteeing the quality that is expected from an educational innovation.

The research study on the iterative development of a TLS on APM represents a contribution to the framework of design and development of TLSs, by reporting the process of refinement of the sequence and its implications on students' realization during the implementation of consecutive refined versions of the sequence.

In order to enhance the quality of a designed educational material it is worth doing an in-depth analysis of students' performance and teachers' needs during its classroom implementation as well as an analysis of the alignment between intended design principles and the learning activities actually designed.

The research also provides a categorization of the types of problematic aspects identified during the implementation of the innovative sequence and the associated types of changes that can be introduced in the sequence in order to overcome some specific difficulties. This typology of changes can be applied to the development of other teaching/learning sequences on different topics.

Finally, another relevant result from this research consists of the refined research-based teaching/learning sequence on Acoustic Properties of Materials (Pintó et al., 2009) that teachers can use in their science classes.

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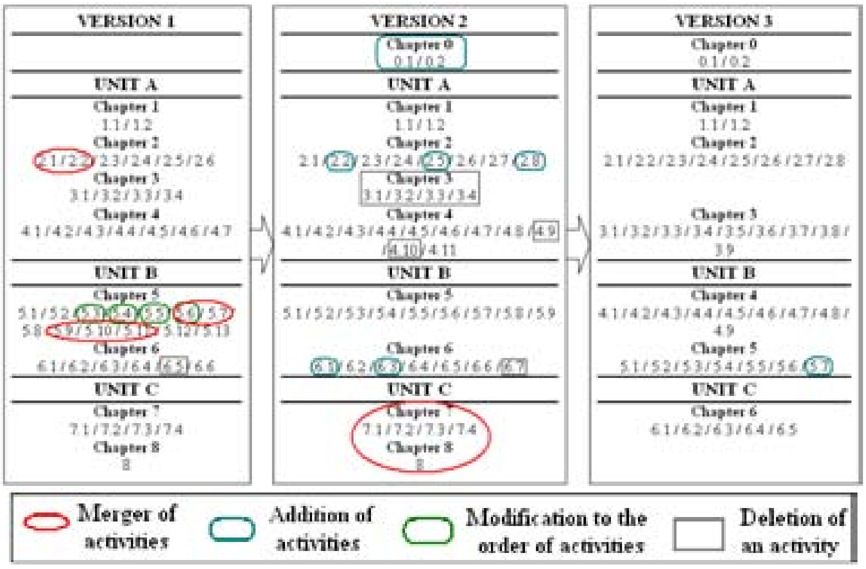
Appendix - Outline of the evolution of the structure of the TLS on APM after consecutive refinements



SECCIÓ III. RESULTATS I CONCLUSIONS

Discussió dels resultats de recerca

Conclusions finals i implicacions

Capítol 7

Discussió dels resultats de recerca

El present treball de tesi ha examinat diverses etapes del procés de desenvolupament iteratiu d'una SEA sobre propietats acústiques dels materials, com són:

- El disseny basat en resultats de recerca (Publicacions 1 i 2)
- L'avaluació i el refinament de la SEA (Publicació 3)
- L'avaluació de la SEA i el desenvolupament de principis de disseny de la mateixa (Manuscrit no publicat)

7.1. Resultats del disseny basat en resultats de recerca de la SEA sobre propietats acústiques dels materials

Les publicacions 1 i 2 informen de dos aspectes diferents d'un mateix procés, com és el del disseny basat en resultats de recerca d'una SEA sobre propietats acústiques dels materials. Partint del model de reconstrucció educativa (Duit *et al.*, 2005), aquestes dues publicacions justifiquen l'estructura conceptual i el tractament dels conceptes i models conceptuals al llarg de la SEA.

La publicació 1 aborda el procés de construcció de l'estructura del contingut a ensenyar en base als resultats de recerca sobre concepcions dels alumnes. En particular, la publicació dóna compte de les concepcions d'una població d'alumnes de secundària (4t d'ESO i 2n de Batxillerat) sobre el fenomen de l'atenuació del so i el comportament acústic dels materials. Aquests alumnes no havien rebut cap ensenyament formal sobre aquest tema però havien experimentat la capacitat d'atenuació acústica de diversos materials mitjançant un muntatge experimental. Els resultats d'aquest estudi mostren que l'escenari de la recerca va ser prou ric per fer emergir múltiples punts de vista tot i que la majoria dels alumnes no sostenen concepcions coherents amb el punt de vista científic. A continuació, discutim els principals resultats presentats a la publicació 1.

Respecte a les concepcions sobre l'atenuació del so que els alumnes expressen, els resultats mostren que la majoria dels alumnes concep el fenomen de l'atenuació del so com una dificultat per transmetre el so a través d'un material. Aproximadament una quarta part dels alumnes conceptualitza els materials aïllants acústics com a barreres que eviten el pas del so i, en conseqüència, consideren la reflexió com l'únic mecanisme d'atenuació del so. Un menor nombre d'alumnes reconeix l'absorció com a mecanisme d'atenuació del so dins d'un material. En alguns casos, els alumnes consideren que l'atenuació del so va acompanyada per la variació d'algunes de les seves característiques, com la seva energia o la seva velocitat de propagació al llarg d'un medi.

Els resultats d'aquest estudi també van evidenciar que les concepcions prèvies (a cap instrucció formal) dels alumnes sobre l'atenuació del so posen en relleu les seves concepcions de la naturalesa i propagació del so. En aquest sentit, les respostes d'alguns alumnes mostren que la concepció més comuna consisteix en considerar el so com una substància física que pot travessar un objecte material o no depenent de determinades característiques d'aquest material. Aquesta concepció correspon al ''model entitat de so'' descrit per Hrepic *et al.* (2010).

Els resultats de la publicació 1 també indiquen les concepcions dels alumnes sobre les propietats i estructura interna dels materials que afecten al comportament acústic dels mateixos. Aquestes concepcions semblen fonamentar-se en els seus models mentals de l'atenuació del so. Així doncs, una mateixa propietat d'un material és concebuda per alguns alumnes com un facilitador i per altres com un obstacle per absorbir o per reflectir so, depenent del model d'atenuació del so que tinguin aquests alumnes. Per exemple, els estudiants que interpreten l'atenuació del so com a resultat d'evitar l'entrada del so a través d'un material consideren que els materials aïllants acústics són densos i no porosos. En canvi, els alumnes que interpreten l'atenuació del so com a resultat de l'absorció per part del material consideren que els materials aïllants acústics són poc densos i porosos.

Els resultats d'aquesta publicació 1 també il·lustren que els alumnes no distingeixen entre propietats dels materials, com la densitat, la compactació o la porositat, utilitzant així indistintament els diferents termes. Els resultats d'aquest estudi són coherents amb els de recerques prèvies com la que va portar a terme Linder (1993), qui ja discutia la simplificació que fan els alumnes de la relació entre propietats dels materials i la seva estructura interna.

Dins del paradigma del disseny basat en la recerca, aquest estudi no només contribueix a aclarir les concepcions dels alumnes sobre l'atenuació del so i el comportament acústic dels materials, sinó que a més dóna suport a les decisions preses en dissenyar una SEA sobre propietats acústiques dels materials. En concret, algunes activitats de la SEA es van dissenyar tenint en compte les respostes donades pels alumnes en aquest estudi, per tal de facilitar l'explicitació de les concepcions de futurs alumnes.

A més, vam tenir en compte les diferències entre el contingut a ensenyar (Hernández *et al.*, 2011, b) i les concepcions dels alumnes evidenciades en aquest estudi per tal d'establir els requeriments d'aprenentatge (Leach i Scott, 2002) per alumnes de 15-16 anys. Aquests requeriments d'aprenentatge assumeixen que els alumnes arribin a:

- Entendre la naturalesa i propagació dels so com un esdeveniment o procés en comptes de com a una entitat.
- Concebre l'atenuació del so com un procés de dissipació de l'energia que implica reflexió i absorció més que com un efecte causat per materials que "obstaculitzen l'entrada del so" o "capturen so".
- Conceptualitzar adequadament les propietats acústiques dels materials, tant a nivell macroscòpic com a nivell microscòpic, i relacionar-les amb els comportament acústic dels materials. Això implicaria, per exemple, considerar la densitat d'un material sòlid com una propietat relacionada amb la massa i l'empaquetament de les seves partícules en comptes d'associar-la amb la distància entre partícules.

Finalment, aquest estudi va proporcionar orientació per organitzar el contingut a ensenyar a la SEA per tal de facilitar el desenvolupament de marcs conceptuals més coherents per part dels alumnes:

- Tenint en compte que les concepcions dels alumnes sobre l'atenuació del so es basen en les seves concepcions sobre la naturalesa i la propagació del so, considerem que l'ensenyament formal sobre la propagació de les ones sonores hauria de ser un prerequisit de la SEA sobre propietats acústiques del materials.
- De manera similar, tenint en compte que les propietats i estructura interna que els alumnes associen amb el comportament acústic dels materials sovint es basa en les seves concepcions sobre l'atenuació dels so en materials, vam decidir desenvolupar primer aquestes en termes de l'energia i distingint el mecanisme de reflexió del so i el d'absorció del so. D'aquesta manera, els alumnes estarien en posició d'identificar dos tipus de materials aïllants acústics (reflectors i absorbents acústics) i d'atribuir-los diferents propietats acústiques.
- Com que la visió dels alumnes de la relació entre propietats i estructura interna dels materials tendeix a ser inadequada o simplificada, vam decidir tractar explícitament aquestes relacions dissenyant tasques i analogies per desenvolupar la comprensió dels alumnes de les propietats acústiques dels materials superant algunes ambigüitats.

En resum, la publicació 1 presenta una possible estructura dels continguts sobre propietats acústiques dels materials per ensenyar-los a secundària. Sens dubte, aquesta estructura es fonamenta, d'una banda, en els resultats de la recerca empírica presentada a la publicació 1 i, d'altra banda, en els objectius d'aprenentatge que, com a autors, perseguim amb el disseny i implementació de la SEA.

La publicació 2 també contribueix a l'anàlisi de l'estructura dels continguts a ensenyar. En concret, aquesta publicació està destinada a aclarir el contingut a ensenyar i la seva rellevància educativa. Aquesta anàlisi es basa en l'estudi de manuals i publicacions clau sobre el tema de les propietats acústiques dels materials que permetin, d'una banda, aclarir quins són els continguts elementals a ensenyar i, d'altra banda, aportar contextos i experiències significatives per a l'aprenentatge d'aquests continguts. En aquest sentit, aquesta publicació no dóna compte dels resultats d'una recerca empírica sinó dels resultats d'una revisió bibliogràfica i d'una anàlisi crítica, que consistí en la selecció dels termes i conceptes clau a partir dels manuals i publicacions de caire més tècnic i en la seva posterior adaptació per ensenyar el contingut tractat a alumnes de secundària.

Aquesta transposició didàctica dels continguts a ensenyar a alumnes de 4t d'ESO, de la que dóna compte la publicació 2, parteix de diverses fonts especialitzades sobre control de soroll ambiental i sobre acústica arquitectònica, per tal d'entendre com optimitzar o evitar el soroll ambiental en sales i edificis de tot tipus, segons les seves necessitats acústiques. D'altra banda, aquesta revisió també té en compte estudis sobre les característiques dels materials que juguen un paper en el seu comportament acústic. Així doncs, la publicació 2 presenta les principals idees resultants de la revisió bibliogràfica i de la reconstrucció educativa dels continguts a ensenyar a alumnes de 4t d'ESO sobre el tema de l'atenuació del so i de les propietats acústiques dels materials. Les principals idees que vam seleccionar com a continguts de la SEA dissenyada es presenten a continuació:

- El fenomen de l'atenuació del so es defineix en termes del nivell d'intensitat sonora com a magnitud física mesurable i s'interpreta en termes de l'energia com a magnitud física abstracta. Considerem que l'atenuació del so a través d'objectes materials implica la reducció del nivell d'intensitat sonora en una banda de l'objecte (so transmès) respecte a l'altra (so incident). També interpretem aquest fenomen en termes de la dissipació de l'energia del so incident en distribuir-se entre el so reflectit, l'energia absorbida dins del material i el so transmès. L'atenuació del so és doncs considerada com el resultat de la reflexió i de l'absorció. Segons això, distingim dos tipus de materials aïllants (o atenuadors) acústics segons el seu comportament acústic: els materials reflectors acústics i els materials absorbents acústics, respectivament.

- El comportament acústic dels materials depèn de determinades propietats físiques, anomenades propietats acústiques, com són: la densitat, la rigidesa i la porositat. Els materials reflectors acústics solen ser densos, rígids i poc o gens porosos (o amb porus tancats), mentre que els materials absorbents acústics solen ser poc densos, flexibles i porosos (amb porus oberts).
- Com que les propietats físiques dels materials depenen de l'estructura interna dels mateixos, interpretem també el comportament acústic dels materials en termes de la seva estructura interna. En aquest sentit, la densitat dels materials és concebuda com una propietat macroscòpica que depèn de la massa i empaquetament de les partícules que formen els materials. La rigidesa és concebuda com la propietat relacionada amb la força dels enllaços entre partícules que formen el material. Finalment, la porositat és deguda a la presència de partícules d'aire dins dels porus o cavitats de l'esquelet sòlid del material, alhora format per altres tipus de partícules.

7.2. Resultats del refinament iteratiu de la SEA sobre propietats acústiques dels materials

La publicació 3 analitza el procés de refinament de la SEA sobre propietats acústiques dels materials al llarg de tres iteracions que comprenen disseny, implementació, avaluació i redisseny (o refinament).

D'una banda, aquesta anàlisi consisteix en la identificació i caracterització dels tipus de dificultats específiques dels alumnes i/o necessitats dels professors per a cada activitat de cadascuna de les tres versions de la SEA sobre propietats acústiques dels materials durant la seva implementació a classe. Com diu Heron (2003, a, p. 354), "la decisió de discutir els resultats dels alumnes en termes de dificultats reflecteix el nostre enfocament de caire pràctic i orientat a la instrucció ja que la identificació d'una dificultat ens proporciona un objectiu d'ensenyament". D'acord amb aquesta afirmació, vam analitzar els resultats de cadascuna de les activitats realitzades a classe al llarg de la implementació de cada versió de la SEA en termes de les dificultats identificades en les mateixes.

Els tipus de dificultats dels alumnes que vam evidenciar amb major o menor presència a les implementacions de les versions consecutives de la SEA són les següents:

- **Dificultats relacionades amb aspectes de metacognició** (DM), quan els alumnes no identifiquen el propòsit d'una pregunta o enunciat, o quan no qüestionen les seves pròpies idees davant d'altres punts de vista presentats en activitats on se'ls demana que analitzin o avaluïn críticament les seves idees en base a altres.
- **Dificultats relacionades amb les imatges de la SEA** (DI), quan els alumnes no interpreten adequadament el significat d'una representació visual, imatge o gràfica, que està relacionada amb un determinat concepte o fenomen.

- **Dificultats relacionades amb els conceptes o models conceptuals** (DC), quan els alumnes no apliquen adequadament[5] un model conceptual o no atribueixen un significat adequat (és a dir, coherent amb la perspectiva científica) a un cert concepte quan prediuen, interpreten o expliquen un fenomen.
- **Dificultats relacionades amb els experiments** (DE), quan els alumnes no fan un adequat control de les variables d'un experiment, no avaluen les limitacions d'un experiment quan el dissenyen i el planifiquen, no interpreten adequadament les magnituds o valors de les mesures que volen prendre amb un instrument o no analitzen adequadament les dades experimentals que recullen.
- **Altres tipus de dificultats** (DO), quan els alumnes no estan familiaritzats amb els procediments d'un cert tipus d'activitat a classe i no donen una resposta escrita en els seus dossiers.

Basant-nos en aquestes dificultats, vam interpretar i caracteritzar els aspectes de cada versió de la SEA que podem considerar problemàtics. Després d'inferir els aspectes problemàtics de cada versió de la SEA després de cada implementació, vam procedir a introduir una sèrie de modificacions al materials dels alumnes de la SEA. Els tipus de canvis que vam introduir en les dues primeres versions de la SEA en redissenyar-les són els següents:

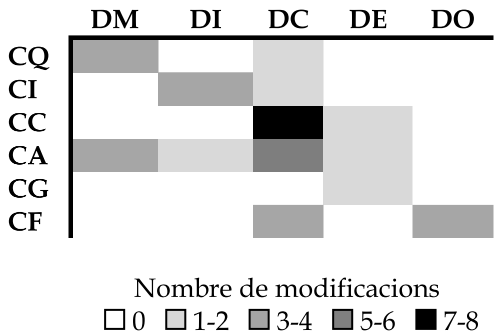
- Reformulació de **preguntes i enunciats** de les activitats de la SEA (CQ)
- Reelaboració de **diagrames, gràfiques i imatges** o introducció de més **representacions visuals** i explicitació del seu significat (CI)
- Introducció de **conceptes** addicionals i **analogies** o adaptació de la **terminologia** emprada (CC)

[5] Per aquesta anàlisi no vam tenir en compte les dificultats conceptuals evidenciades en preguntes o activitats d'exploració d'idees prèvies, ja que considerem que aquestes activitats tenen precisament aquesta finalitat: fer emergir les dificultats dels alumnes per tractar de superar-les al llarg de la SEA.

- Addició o supressió de certes **activitats**, reelaboració de **l'enfocament** de certes activitats o canvis en **l'estructura** de la SEA (ordre de les activitats) (CA)
- Addició **d'orientacions** o **especificacions** sobre com fer una activitat particular (CG)
- Modificacions en el **format d'edició** del material escrit dels alumnes (CF)

Per tal d'identificar possibles patrons de modificació que ens permetessin descriure aspectes del refinament de la SEA, vam analitzar les relacions que existeixen entre els tipus de dificultats identificades i els tipus de modificacions introduïdes a la primera versió de la SEA per tractar de superar aquestes dificultats. Per això, vam analitzar el nombre i tipus de canvis introduïts a la primera versió de la SEA en funció dels tipus de dificultats dels alumnes que es pretenien superar amb els canvis. Aquest tipus d'anàlisi està resumit a la taula 2.

Taula 2. Relació dels tipus de canvis introduïts a la primera versió de la SEA i els tipus de dificultats dels alumnes identificades



L'anterior taula posa en relleu alguns aspectes del procés de refinament de la SEA dissenyada:

- El tipus de dificultats dels alumnes que ha donat peu a més modificacions en la SEA són les dificultats relacionades amb l'aplicació de conceptes i models conceptuals per part dels alumnes (DC).
- El tipus de modificació més freqüentment introduïda a la SEA ha estat el canvi en l'enfocament, ordre o estructura de les activitats (CA).

- Amb la intenció de superar les dificultats dels alumnes relacionades amb aspectes metacognitius (DM), es van introduir a la SEA principalment dos tipus de canvis: canvis en les preguntes i enunciats de les activitats (CQ) i canvis en l'enfocament, ordre o estructura de les activitats (CA). Aquests canvis anaven doncs destinats a facilitar als alumnes la identificació del propòsit d'una determinada pregunta o a adaptar el nivell d'exigència que es requeria dels alumnes o el suport proporcionat als mateixos per realitzar l'activitat.
- Les dificultats dels alumnes relacionades amb la interpretació del significat de les imatges (DI) van ser tractades principalment refent diagrames, gràfiques i imatges o introduint més representacions visuals i explicitant el seu significat (CI).
- Per tal de superar les dificultats conceptuals dels alumnes (DC), principalment vam introduir dos tipus de canvis: explicitació del significat científic de certs conceptes (CC), distingint-lo del seu significat quotidià, i modificació de l'enfocament d'algunes activitats (CA) per tal de donar un suport adequat al procés de construcció de models conceptuals per part dels alumnes.
- Per tal d'abordar les dificultats dels alumnes relacionades amb les activitats experimentals (DE), vam introduir diversos tipus de canvis a la SEA: adaptació de l'enfocament de les activitats (CA), introducció de conceptes específics (CC) i adaptació del grau de guia o de les especificacions sobre els procediments d'una activitat (CG).
- Finalment, altres dificultats (DO) identificades durant la implementació de la SEA, com la manca de respostes escrites dels alumnes als dossiers, van abordar-se modificant l'enfocament de les activitats (CA) per adaptar la demanda als alumnes o adaptant el format d'edició de les activitats (CF) als dossiers.

La publicació 3 també analitza les forces impulsores de canvis o motius crítics per introduir cadascun dels canvis a cada versió de la SEA durant el procés d'avaluació i refinament de les mateixes. Aquestes forces impulsores de canvis es basen en els criteris d'avaluació de la qualitat d'innovacions de van den Akker (1999) i es resumeixen en les següents:

- Necessitat de reajustar o readaptar les activitats als "principis de disseny" de la SEA per tal d'augmentar la seva **validesa** (DF1). Tot i que el disseny de la SEA es va fonamentar en principis teòrics i resultats empírics de recerques prèvies, alguns dels canvis introduïts a la SEA durant el procés de refinament van fer-se en base a una anàlisi crítica de la SEA implementada per augmentar la consistència interna entre les diferents parts de la SEA d'acord amb els principis de disseny seguits. Com a exemple, totes les modificacions en la seqüenciació o organització de les activitats es van fer tenint en compte l'estructura dels continguts planificada per la SEA amb la finalitat d'agrupar o reorganitzar les activitats que abordessin el mateix concepte o fenomen.
- Necessitat d'atendre les necessitats o dificultats dels professors per tal d'augmentar la **practicitat / utilitat** de la SEA dissenyada (DF2). El fet que la majoria de professors que van implementar la SEA també participessin en el seu disseny possiblement haurà tingut un efecte positiu en la seva percepció de la utilitat del material. No obstant, les observacions de classe i les converses durant les reunions del grup de treball format per professors de secundària i investigadors també van evidenciar algunes dificultats dels professors per comprendre els propòsits de certes activitats i, en conseqüència, per proporcionar orientacions adequades als alumnes per realitzar una certa tasca. A part de comentar aquestes dificultats a les reunions, també es van adaptar les activitats considerades més problemàtiques pels professors per facilitar-los la seva tasca docent. El refinament d'aquestes activitats va contribuir a millorar la practicitat percebuda de la SEA, valorada per professors involucrats i no involucrats en el disseny de la mateixa.
- Necessitat d'atendre les necessitats o dificultats dels alumnes per tal de millorar **l'eficàcia** de la SEA **(**DF3). L'avaluació de l'eficàcia de la SEA es

va fer en base a l'anàlisi del grau de consistència entre les experiències i resultats de la intervenció i els objectius anticipats. Tal i com s'ha discutit abans, l'anàlisi de les necessitats o dificultats dels alumnes va resultar en modificacions de diferents aspectes de la SEA adreçades a superar aquestes dificultats i millorar els resultats d'aprenentatge dels alumnes en futures implementacions.

Analitzant el pes de cadascuna d'aquestes raons per introduir canvis a la SEA, podem dir que la majoris dels canvis es van introduir per dues raons principals: (i) superar les necessitats o dificultats dels alumnes o millorar l'eficàcia de la SEA (DF3), i (ii) "alinear" les activitats de la SEA als principis de disseny de la mateixa o augmentar la seva validesa (DF1). Moltes menys modificacions van ser considerades necessàries per donar suport als professors o per augmentar la utilitat de la SEA (DF2).

Finalment, la publicació 3 avalua la qualitat del refinament de la SEA comparant els tipus i prevalença de les dificultats dels alumnes al llarg de versions consecutives de la SEA. Aquesta avaluació es va fer tenint en compte el nombre de dificultats de cada tipus i, en conseqüència, el nombre de canvis de cada tipus introduïts a cada versió de la SEA després de cada implementació. La figura 2 presenta un histograma que mostra el nombre i tipus de les dificultats dels alumnes identificades després de la implementació de les tres versions de la SEA. Aquesta representació gràfica mostra l'evolució de les dificultats dels alumnes com a resultat de l'avaluació i refinament de versions consecutives de la SEA.

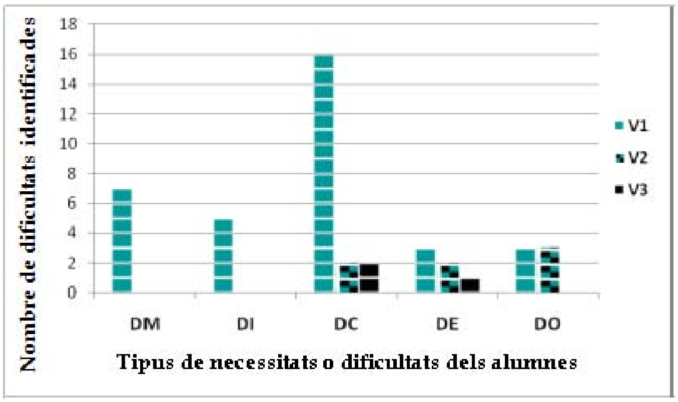


Figura 2. Evolució de la prevalença de les dificultats dels alumnes al llarg de la implementació de tres versions consecutives de la SEA

Tal com mostra la figura 2, s'observa una progressió gradual cap a la millora de l'eficàcia de versions consecutives de la SEA, ja que a cada implementació es va evidenciar un menor nombre de dificultats dels alumnes, però especialment s'observa una important superació de les dificultats de tipus conceptual (DC) de la primera a la segona implementació de la SEA.

L'anàlisi de la prevalença de cada tipus de canvi introduït a la SEA després de cada cicle d'implementació, avaluació i refinament també ens porta a resultats similars respecte a la millora gradual de l'eficàcia de la SEA. La figura 3 mostra l'evolució en nombre i tipus de canvis introduïts durant el refinament de les dues primeres versions de la SEA. Aquest histograma mostra que es van considerar necessàries menys modificacions a la segona versió de la SEA en comparació amb la primera versió.

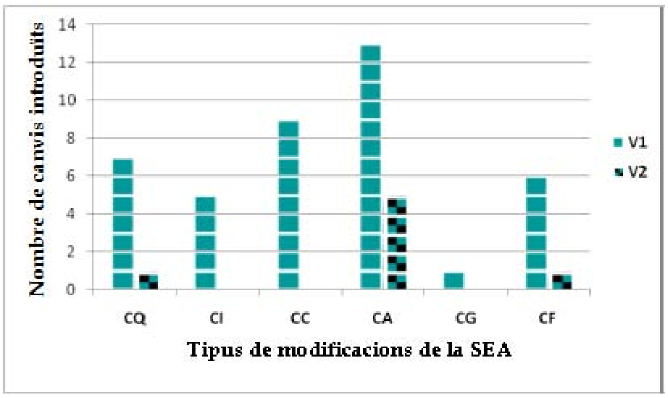


Figura 3. Evolució dels canvis introduïts durant el refinament de les dues primeres versions de la SEA

7.3. Resultats de l'avaluació de l'eficàcia de la SEA quant al desenvolupament de models mentals dels alumnes

L'article 4 (manuscrit no publicat) presenta l'anàlisi de l'eficàcia de l'última versió de la SEA respecte als objectius d'aprenentatge conceptuals que s'esperava que els alumnes assolissin al final de la seva participació en la implementació de la SEA. Aquesta anàlisi de l'eficàcia de la SEA es va portar a terme considerant els resultats d'aprenentatge dels alumnes durant i al final de la SEA. Tenint en compte que els objectius d'aprenentatge conceptuals que s'esperaven obtenir al final de la implementació de la SEA sobre propietats acústiques dels materials es concreten en el desenvolupament de tres models conceptuals per part dels alumnes, l'anàlisi de les respostes dels alumnes al llarg de la implementació de la SEA ens ha permès caracteritzar els seus processos de modelització (o construcció i aplicació de models conceptuals). Els tres models conceptuals a desenvolupar al llarg de la SEA sobre propietats acústiques dels materials són els següents:

- Un model conceptual teòric del fenomen de l'atenuació del so en materials en termes de l'energia (CM1)
- Un model conceptual empíric del comportament acústic dels materials en termes de les seves propietats físiques (CM2)
- Un model conceptual teòric del comportament acústic dels materials en termes de la seva estructura interna (CM3)

Cadascun d'aquests models conceptuals a desenvolupar pels alumnes al llarg de la SEA es va expressar en termes d'un conjunt d'objectius d'aprenentatge específics en un format avaluable. Identificant els objectius d'aprenentatge que els alumnes assoleixen a cada moment de la implementació i agrupant els que una majoria dels alumnes assoleix, vam poder descriure els models mentals inicials, intermedis i finals dels alumnes. D'aquesta manera, vam poder caracteritzar els models mentals dels alumnes a cada etapa del procés d'aprenentatge, i també la prevalença de cada model mental a cada etapa de la implementació. En definitiva, vam descriure les etapes de progrés (Corcoran, Mosher i Rogat, 2009) que caracteritzen els passos o estadis en el desenvolupament de models mentals cada vegada més propers als models conceptuals esperats. En paraules de Duschl *et al.* (2011), vam poder inferir les progressions d'aprenentatge "de baix a dalt"[6], que descriuen el desenvolupament dels alumnes de cada model conceptual.

Analitzant el grau de desenvolupament dels models mentals dels alumnes en diferents moments al llarg de la implementació de la SEA, vam poder: (i) avaluar l'eficàcia de la seqüència comparant els resultats d'aprenentatge dels alumnes al final de la implementació amb el seu punt de partida a l'inici, i (ii) identificar quins models mentals dels alumnes són predominants a cada moment de la implementació.

7.3.1. *Etapes de desenvolupament dels models conceptuals CM1, CM2 i CM3 per part dels alumnes al llarg de la SEA*

Model conceptual 1 (CM1)

Respecte al model conceptual de l'atenuació del so en termes de l'energia (CM1), l'anàlisi de les respostes dels alumnes a diverses activitats al llarg de la SEA ens va permetre caracteritzar quatre models mentals dels alumnes, que representen diferents estadis en el procés de desenvolupament del CM1 per part dels alumnes. La Taula 3 presenta la descripció d'aquests estadis.

[6] Aquesta progressió d'aprenentatge es basa en l'avaluació de les evidències d'aprenentatge dels alumnes, en comptes de basar-se només en una anàlisi del contingut i en l'experiència docent.

Taula 3. Descripció dels estadis de desenvolupament del CM1

Estadi de desenvolupament del CM1	Descripció de cada model mental
S1 (Model mental inicial)	Els alumnes expliquen l'atenuació del so en un material com la reducció del nivell d'intensitat sonora resultant de la distribució del so en diferents components - el so transmès i el so reflectit
S2 (Model intermedi 1)	Els alumnes expliquen l'atenuació del so en un material com la reducció del nivell d'intensitat sonora resultant de la distribució del so en diferents components - el so transmès i el so absorbit
S3 (Model intermedi 2)	Els alumnes expliquen l'atenuació del so en un material com la reducció del nivell d'intensitat sonora resultant de la distribució del so en diferents components - el so transmès, el so reflectit i el so absorbit
S4 (Model conceptual)	Els alumnes expliquen l'atenuació del so en un material com la reducció del nivell d'intensitat sonora resultant de la distribució de l'energia del so en diferents components - l'energia del so transmès, l'energia del so reflectit i l'energia absorbida

Després de caracteritzar cada estadi de desenvolupament del CM1, vam analitzar la distribució d'alumnes que es troben a cada estadi de desenvolupament del CM1 al llarg de la implementació de la SEA. La figura 4 representa aquesta distribució.

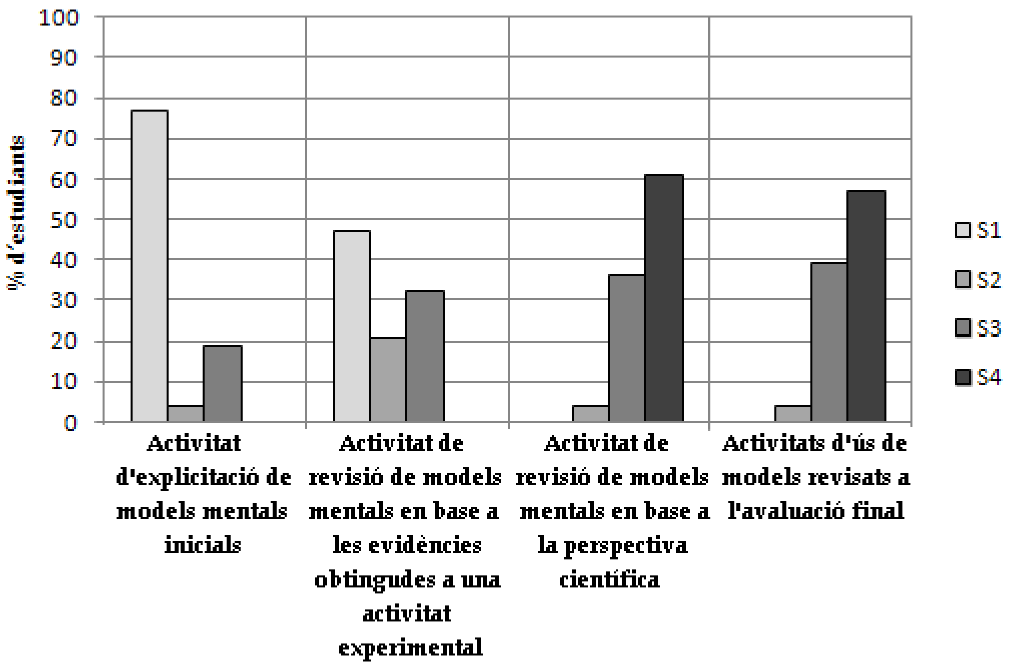


Figura 4. Desenvolupament del model conceptual CM1 per part dels alumnes al llarg de la SEA

Tal com mostra la figura 4, a l'inici de la implementació de la SEA (activitat d'explicitació de models mentals inicials) la majoria d'alumnes (77%) va explicitar el model mental inicial sobre l'atenuació del so en materials (S1). Considerem aquest model mental inicial com el punt de partida (majoritari) en el procés de desenvolupament del CM1.

Després d'una activitat experimental i d'una activitat de tractament d'unes dades proporcionades, es va demanar als alumnes que interpretessin una situació quotidiana (com s'atenua el so a través de les parets d'un edifici). Tal com mostra la figura 4, sembla que aquestes activitats van promoure la revisió dels models mentals inicials en base a les evidències obtingudes a l'activitat experimental ja que s'aprecia una lleugera progressió dels models mentals dels alumnes de l'atenuació del so cap a estadis més elaborats (S2 o S3).

A continuació, es va introduir als alumnes el punt de vista de la ciència sobre l'atenuació del so en materials mitjançant un text escrit en els seus dossiers de classe i una discussió amb tot el grup classe i el professor. Segons els resultats representats a la figura 4, aquesta activitat de discussió del punt de vista científic va tenir un important efecte positiu en les respostes dels alumnes a activitats posteriors del dossier, promovent la revisió dels models mentals dels alumnes, ja que s'observa que la majoria dels alumnes (61%) va assolir l'estadi més desenvolupat (S4) de la progressió del model conceptual sobre atenuació del so en materials (CM1).

Les preguntes de l'avaluació final, realitzada unes dues setmanes després de l'activitat anterior, revelen que aproximadament un 60% dels alumnes van ser capaços de desenvolupar el model conceptual de l'atenuació del so en materials que correspon a la versió més elaborada (S4). Gairebé el 40% restant dels alumnes va respondre l'avaluació final expressant un model d'atenuació del so en materials apropiat però sense fer referència al concepte d'energia (S3).

Model conceptual 2 (CM2)

Respecte al model conceptual del comportament acústic dels materials en termes de les seves propietats físiques (CM2), l'anàlisi de les respostes dels alumnes a diverses activitats al llarg de la SEA ens va permetre caracteritzar quatre models mentals dels alumnes, que representen diferents estadis en el procés de desenvolupament del CM2 per part dels alumnes. La Taula 4 presenta la descripció d'aquests estadis.

Taula 4. Descripció dels estadis de desenvolupament del CM2

Estadi de desenvolupament del CM2	Descripció de cada model mental
S1 (Model mental inicial)	Els alumnes expliquen i prediuen el comportament acústic dels materials en termes de propietats intensives i extensives, com la densitat i la rigidesa, tot i que aquests termes no s'utilitzen amb un significat apropiat des del punt de vista científic
S2 (Model intermedi 1)	Els alumnes expliquen i prediuen el comportament acústic dels materials en termes de propietats intensives i extensives, com la densitat, la rigidesa i la porositat, tot i que aquests termes no s'utilitzen amb un significat apropiat des del punt de vista científic
S3 (Model intermedi 2)	Els alumnes expliquen i prediuen el comportament acústic dels materials en termes de propietats intensives i extensives, com la densitat, la rigidesa i la porositat, utilitzant aquests termes amb un significat apropiat des del punt de vista científic
S4 (Model conceptual)	Els alumnes expliquen i prediuen el comportament acústic dels materials únicament en termes de les propietats intensives densitat, rigidesa i porositat, utilitzant aquests termes amb un significat apropiat des del punt de vista científic

Després de caracteritzar cada estadi de desenvolupament del CM2, vam analitzar la distribució d'alumnes que es troben a cada estadi de desenvolupament del CM2 al llarg de la implementació de la SEA. La figura 5 representa aquesta distribució.

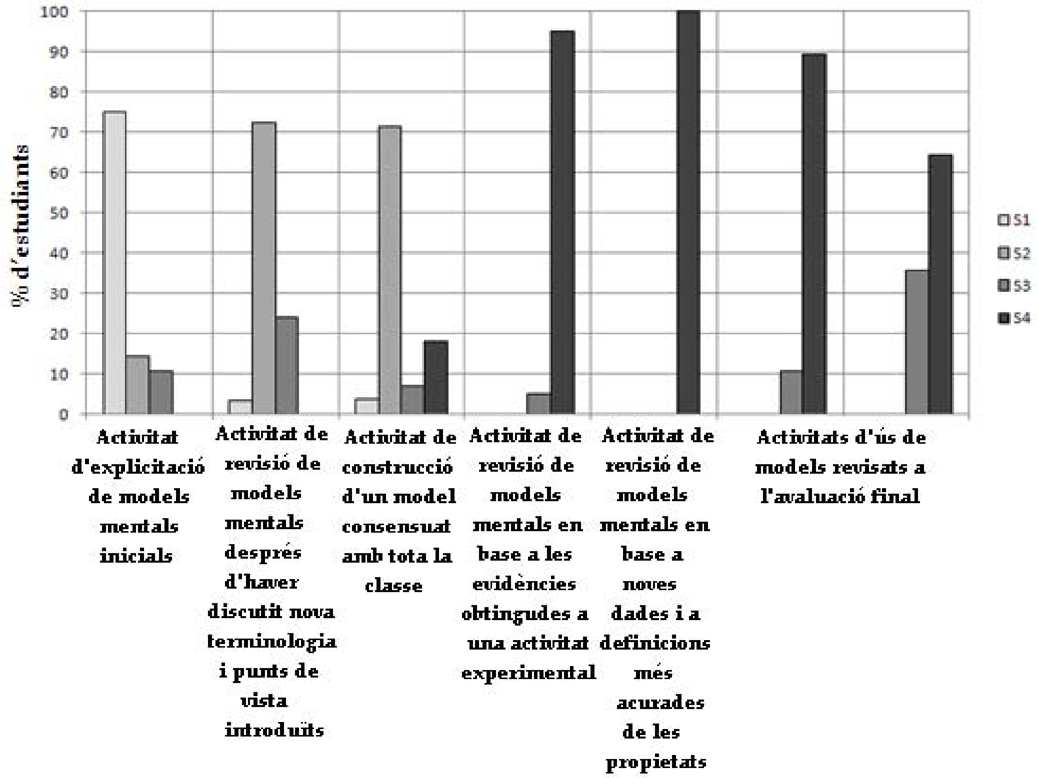


Figura 5. Desenvolupament del model conceptual CM2 per part dels alumnes al llarg de la SEA

A la figura 5 podem observar que el punt de partida de la majoria dels alumnes (75%) és el primer estadi de desenvolupament de models mentals (S1) descrit a la taula 4. Després d'introduir a la classe nova terminologia i punts de vista alternatius i de discutir-los en petits grups, un major nombre d'alumnes va començar a reconèixer la porositat com una propietat acústica. Tot i que els alumnes mencionessin les tres propietats que afecten el comportament acústic dels materials (densitat, rigidesa i porositat), la majoria d'ells (més del 70%) tendien a atorgar un significat poc adequat a certs termes científics i a associar moltes altres característiques amb el comportament acústic dels materials (S2). Després de discutir a classe les respostes dels alumnes i arribar a un model consensuat, la majoria d'alumnes va coincidir en aquest segon estadi de desenvolupament dels seus models mentals (S2).

Els resultats mostren que després que els alumnes portessin a terme l'experiment per determinar el comportament acústic de certs materials, pràcticament la totalitat dels alumnes (95%) va ser capaç d'explicar adequadament el comportament acústic dels materials únicament en termes de les tres propietats intensives - densitat, rigidesa i porositat, utilitzant aquests conceptes adequadament (S4). A l'avaluació final, la majoria d'alumnes havia desenvolupat el model conceptual esperat (S4) del comportament acústic dels materials en termes de les seves propietats físiques (CM2).

Model conceptual 3 (CM3)

Respecte al model conceptual del comportament acústic dels materials en termes de la seva estructura interna (CM3), l'anàlisi de les respostes dels alumnes a diverses activitats al llarg de la SEA ens va permetre caracteritzar tres models mentals dels alumnes, que representen diferents estadis en el procés de desenvolupament del CM3 per part dels alumnes. La Taula 5 presenta la descripció d'aquests estadis.

Taula 5. Descripció dels estadis de desenvolupament del CM3

Estadi de desenvolupament del CM3	Descripció de cada model mental
S1 (Model mental inicial)	Els alumnes expliquen el comportament acústic dels materials utilitzant el model de partícules de la matèria i descrivint mecanismes d'atenuació del so en materials inadequats segons la perspectiva científica (generalment relacionats amb el "model entitat de so")
S2 (Model híbrid entre S1 i S3)	Els alumnes utilitzen ambdós models - l'inicial (S1) i el conceptual esperat (S3) - a l'hora d'explicar la influència de certes característiques dels materials en el seu comportament acústic
S3 (Model conceptual)	Els alumnes expliquen el comportament acústic dels materials utilitzant el model de partícules de la matèria i descrivint mecanismes d'atenuació del so en materials apropiats segons la perspectiva científica

Després de caracteritzar cada estadi de desenvolupament del CM3, vam analitzar la distribució d'alumnes que es troben a cada estadi de desenvolupament del CM3 al llarg de la implementació de la SEA. La figura 6 representa aquesta distribució.

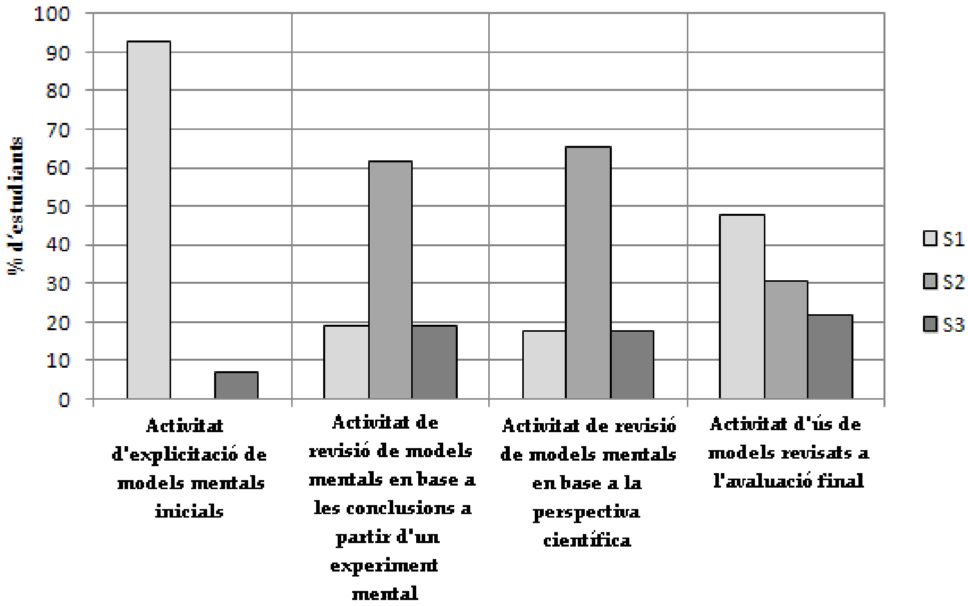


Figura 6. Desenvolupament del model conceptual CM3 per part dels alumnes al llarg de la SEA

Tal com mostra la figura 6, a la pregunta d'exploració i explicitació d'idees prèvies, la majoria dels alumnes (90%) va explicar el comportament acústic dels materials utilitzant el model mental inicial (S1) descrit a la taula 5. Aquest model no és consistent amb la perspectiva científica ja que el so és concebut com una entitat física més que com un procés i, en conseqüència, l'atenuació del so és concebuda com un procés d'obstrucció al pas del so o de captura del so en comptes de ser concebuda com un procés de dissipació d'energia que implica vibració de partícules.

Després que els alumnes portessin a terme un experiment mental, que consistia en investigar la influència de l'estructura interna dels materials en el seu comportament acústic en termes d'un model de boles i molles de la matèria i una analogia que comparava les partícules d'un material amb les boles d'un billar, més del 80% dels alumnes van començar a explicar el comportament acústic dels materials utilitzant el model de partícules de la matèria i descrivint adequats mecanismes d'atenuació del so en materials (S3). Tot i que aquests alumnes utilitzaven el model conceptual esperat per explicar la influència d'algunes propietats en el comportament acústic dels materials en termes de la seva estructura interna, la majoria d'ells van continuar utilitzant els seus models mentals inicials (S1) per explicar la influència d'altres propietats. És a dir, la majoria dels alumnes va utilitzar un model híbrid (S2). Vam evidenciar resultats similars després que els alumnes llegissin i discutissin amb els companys i els professors la perspectiva científica. A l'avaluació final, aproximadament la meitat dels alumnes va respondre en termes dels seus models mentals inicials (S1) mentre que l'altra meitat va utilitzar el model conceptual esperat (S3) o el model híbrid (S2).

7.3.2. *Influència de les activitats de la SEA en el desenvolupament dels models conceptuals CM1, CM2 i CM3 per part dels alumnes*

Amb el propòsit de validar la progressió d'aprenentatge dels alumnes cap a la construcció de cada model conceptual que fos més representativa de la població d'estudi (29 alumnes), vam fer un seguiment de la progressió de cada alumne, per tal d'il·lustrar si aquests experimentaven una progressió, una regressió o no experimentaven cap evolució com a resultat de la realització de diverses activitats clau de la SEA. Aquest procediment també va permetre evidenciar la influència de cadascuna d'aquestes activitats de la SEA sobre el desenvolupament dels alumnes dels tres models conceptuals descrits abans.

Model conceptual 1 (CM1)

La taula 6 mostra els tipus d'evolució experimentats pels alumnes mentre desenvolupaven els seus models d'atenuació del so en materials.

Taula 6. Tipus de progressions d'aprenentatge experimentats pels alumnes en desenvolupar el CM1

Tipus d'evolució dels models mentals dels alumnes	Abans i després de l'activitat experimental	Abans i després d'introduir i discutir a classe el model conceptual esperat	Abans i després d'aplicar els models revisats dels alumnes en activitats posteriors
Progressió	29%	**84%**	26%
Regressió	18%	5%	26%
Cap evolució	**53%**	11%	**48%**

En termes generals, aquests resultats mostren que les activitats que els alumnes realitzen per obtenir noves evidències empíriques i extreure conclusions a partir d'elles, i també les activitats d'ús o aplicació de models mentals revisats abans de l'avaluació final, van promoure una progressió d'aprenentatge modesta (29% i 26% respectivament). D'altra banda, l'activitat que va tenir un major impacte (84%) en el desenvolupament del CM1 per part dels alumnes va ser la discussió a classe entre els alumnes i el professor/a del punt de vista científic sobre l'atenuació del so en materials, que es va introduir mitjançant un text escrit ('Què hi diu la ciència?') sobre com la ciència interpreta aquest fenomen i mitjançant un diagrama que representa com l'energia del so incident es distribueix quan el so arriba a un objecte.

La figura 7 representa la progressió d'aprenentatge predominant cap a la construcció del model conceptual de l'atenuació del so en materials (CM1) al llarg de la implementació de la SEA.

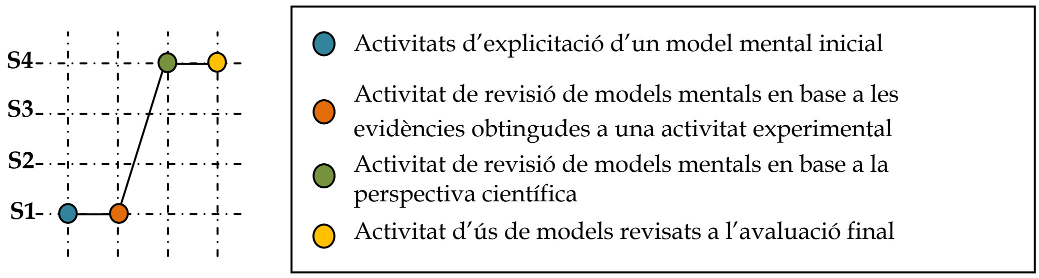


Figura 7. Descripció del procés de desenvolupament del CM1 per part dels alumnes al llarg de la implementació de la SEA

Model conceptual 2 (CM2)

La taula 7 mostra els tipus d'evolució experimentats pels alumnes mentre desenvolupaven els seus models mentals del comportament acústic dels materials en termes de les seves propietats físiques.

Taula 7. Tipus de progressions d'aprenentatge experimentats pels alumnes en desenvolupar el CM2

Tipus d'evolució dels models mentals dels alumnes	Abans i després de discutir a classe nova terminologia i nous punts de vista	Abans i després de construir a la classe un model consensuat	Abans i després de les activitats experimentals	Abans i després d'analitzar dades experimentals proporcionades i discutir a classe el significat de certes propietats	Abans i després d'aplicar els models revisats a activitats posteriors
Progressió	**75%**	28%	**79%**	0%	0%
Regressió	7%	18%	0%	0%	14%
Cap evolució	18%	**54%**	21%	**100%**	**86%**

Tal com es mostra a la taula 7, els resultats posen en relleu que l'activitat de discussió a classe de nova terminologia i nous punts de vista, així com la realització d'un experiment i l'elaboració de conclusions a partir del mateix, són les activitats que van tenir un major impacte sobre el desenvolupament del CM2 per part dels alumnes, ja que s'observa que un 75% i un 79% dels alumnes respectivament va progressar des d'un cert estadi de desenvolupament del model conceptual cap a estadis més avançats després de realitzar aquestes activitats.

La figura 8 representa la progressió d'aprenentatge predominant cap a la construcció del model conceptual del comportament acústic dels materials en termes de les seves propietats físiques (CM2) al llarg de la implementació de la SEA.

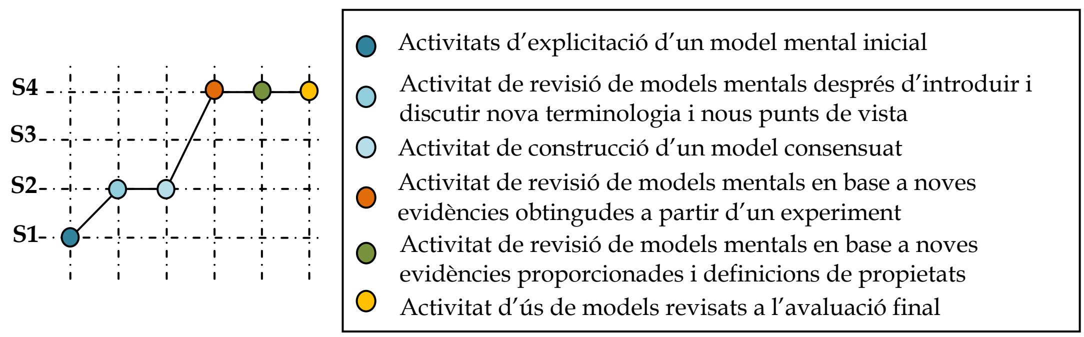


Figura 8. Descripció del procés de desenvolupament del CM2 per part dels alumnes al llarg de la implementació de la SEA

Model conceptual 3 (CM3)

La taula 8 mostra els tipus d'evolució experimentats pels alumnes mentre desenvolupaven els seus models mentals del comportament acústic dels materials en termes de la seva estructura interna.

Taula 8. Tipus de progressions d'aprenentatge experimentats pels alumnes en desenvolupar el CM3

Tipus d'evolució dels models mentals dels alumnes	Abans i després de portar a terme l'experiment mental	Abans i després d'introduir i discutir a classe la perspectiva científica	A l'avaluació final
Progressió	**72%**	29%	21%
Regressió	4%	24%	**53%**
Cap evolució	24%	**48%**	26%

Els resultats que es mostren a la taula 8 posen en relleu que la realització i discussió a classe de l'experiment mental va ser l'activitat que va tenir un major impacte (72%) en promoure la revisió dels models mentals dels alumnes. La discussió a classe de la perspectiva científica no va representar una activitat gaire significativa per promoure la progressió de models mentals ja que quasi la meitat dels alumnes va continuar responent en termes del mateix models abans i després d'aquesta activitat. Finalment, el fet que aproximadament un 50% dels alumnes utilitzés models mentals menys desenvolupats a l'avaluació final pot ser interpretat des de dues perspectives: (1) aquest model conceptual (CM3) pot ser massa complicat pels alumnes d'aquest nivell ja que implica la utilització del model de partícules de la matèria juntament amb els altres dos models tractats a la SEA - CM1 i CM2; (2) la manca d'aplicació d'aquest model conceptual (CM3) en diverses situacions al llarg de la SEA podria haver contribuït a la manca de consolidació d'aquest model al final de la implementació.

La figura 9 representa la progressió d'aprenentatge predominant cap a la construcció del model conceptual del comportament acústic dels materials en termes de la seva estructura interna (CM3) al llarg de la implementació de la SEA.

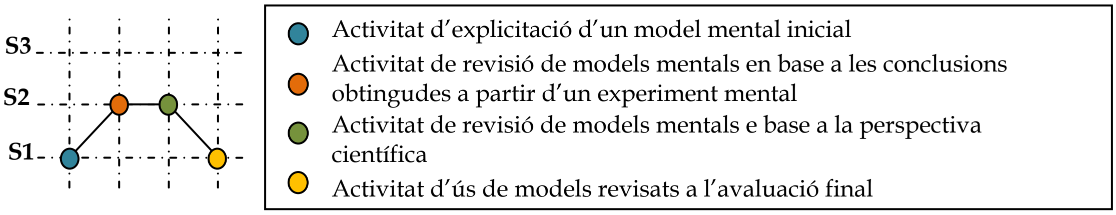


Figura 9. Descripció del procés de desenvolupament del CM3 per part dels alumnes al llarg de la implementació de la SEA

Capítol 8

Conclusions finals i implicacions

A partir dels resultats discutits en el capítol anterior, presentem a continuació algunes conclusions sobre el procés d'avaluació i refinament de seqüències d'ensenyament i aprenentatge i sobre el procés de desenvolupament de principis de disseny. També discutim algunes implicacions per futures recerques i per la pràctica docent i de disseny curricular.

8.1. Sobre el procés d'avaluació i refinament de seqüències d'ensenyament i aprenentatge

L'anàlisi de l'ampli rang de dades recollides, després de dos cicles d'experimentació amb la SEA, ens va permetre avaluar la qualitat de versions consecutives de la SEA sobre propietats acústiques dels materials i identificar els principals aspectes i processos que tenen lloc durant el refinament iteratiu de la mateixa.

En primer lloc, les dades recollides durant la implementació de la SEA van ser analitzades amb l'objectiu d'identificar les dificultats que sorgien durant la implementació a la classe de versions consecutives de la SEA. Podem dir que, fonamentalment, vam identificar dos tipus de dificultats dels alumnes: aquelles que evidencien una manca de progrés dels alumnes cap a l'assoliment de certs objectius d'aprenentatge esperats (per exemple, les dificultats relacionades amb els conceptes o models conceptuals o les dificultats relacionades amb els experiments), i aquelles dificultats que indiquen una realització poc adequada d'una certa activitat i, en conseqüència, un possible factor d'obstaculització en l'assoliment de certs objectius d'aprenentatge esperats (per exemple, les dificultats relacionades amb aspectes de metacognició).

Un resultat notable del procés de desenvolupament iteratiu és la superació de la majoria d'aquestes dificultats. A més, el decreixement del nombre de dificultats dels alumnes a partir del refinament de la primera versió de la SEA és significativament superior al decreixement resultant del refinament de la segona versió de la SEA.

La identificació de dificultats dels alumnes ens va permetre interpretar diversos aspectes problemàtics de la SEA a cada cicle de desenvolupament, la qual cosa és el focus de la *primera pregunta de recerca* d'aquest estudi. Els resultats de la recerca presentada a la tercera publicació que forma part d'aquesta tesi mostren que els principals aspectes de la SEA que van ser interpretats com a problemàtics a la primera iteració van ser l'enfocament i l'organització d'algunes activitats. També vam interpretar com aspectes problemàtics alguns conceptes i analogies seleccionades, alguna terminologia utilitzada i algunes preguntes formulades a la SEA. Aquests aspectes van tenir un pes important en el refinament de la primera versió de la SEA. Comparant el primer i segon cicle d'experimentació de la SEA, vam identificar un menor nombre d'aspectes problemàtics a la segona iteració, la qual cosa indica que el refinament dut a terme va resultar força efectiu. A més, vam identificar diferents patrons a la segona iteració: (i) no només es van considerar problemàtiques menys activitats quant al seu enfocament sinó que a més l'organització de les activitats va ser valorada com adequada, i (ii) la selecció de conceptes, analogies, terminologia i imatges així com les orientacions proporcionades als alumnes sobre com realitzar certes activitats van ser interpretades com a adequades en base a les evidències obtingudes a partir de l'anàlisi previ de les dificultats dels alumnes.

La *segona pregunta de recerca* fa referència als canvis introduïts a la SEA en base als aspectes problemàtics als que van adreçats. Cada tipus de modificació va anar dirigit a tractar de superar cada tipus de dificultat identificada després de la implementació de cada versió de la SEA. Aquesta tipologia de canvis pot ser útil per altres investigadors o dissenyadors de materials a l'hora de desenvolupar i refinar SEAs que abordin altres temàtiques i proposin diferents enfocaments didàctics i recursos.

La *tercera pregunta de recerca* té a veure amb les forces impulsores de canvis o les raons crítiques per modificar certs aspectes de la SEA. No només l'anàlisi de dades dels alumnes sinó també l'anàlisi de dades relacionades amb els professors i el metanàlisi dels principis de disseny de la SEA va donar lloc a diverses raons per justificar la necessitat de certes modificacions de la SEA. Aquestes forces impulsores de canvis han estat relacionades amb els criteris seguits per avaluar la qualitat d'una innovació, descrits per Nieveen (2009), ja que, de fet, els canvis introduïts a cada versió de la SEA anaven adreçats a millorar la qualitat de la mateixa.

En aquest sentit, la millora de l'eficàcia de la SEA al llarg del procés de refinament iteratiu ha estat descrit en termes de l'evolució del nombre i tipus de dificultats dels alumnes i aspectes problemàtics de la SEA. El decreixement en el nombre de dificultats identificades pels alumnes evidencia que el desenvolupament iteratiu de la SEA ha contribuït a millorar l'eficàcia de la SEA, des del punt de vista dels resultats dels alumnes.

D'altra banda, la millora de la validesa de la SEA es va realitzar readaptant-la consistentment amb els principis de disseny de la SEA. El pes que aquesta "força impulsora de canvis" va tenir en el procés de refinament de la SEA posa en relleu la importància d'explicitar i tenir en compte els principis de disseny del grup dissenyador a l'hora de millorar la qualitat de la SEA. Segons Ruthven *et al.* (2009, p.329), "tot i que el refinament iteratiu d'un disseny a través de l'anàlisi de la seva implementació és sens dubte important, la validesa (o rigor) i l'eficiència amb les que aquesta revisió pot ser realitzada són influenciades per la qualitat del disseny original i per la claredat i coherència de les intencions que expressa".

Finalment, la qualitat de la SEA dissenyada va ser també avaluada des del punt de vista de la seva practicitat (o utilitat), en termes de les necessitats dels professors de secundària que van formar part del grup de disseny i van implementar la SEA a les seves classes de ciències. A diferència de la validesa i l'eficàcia, l'avaluació de la practicitat de la primera versió de la SEA va donar lloc a pocs canvis i, a més, no es van introduir canvis en refinar la segona versió de la SEA com a resultats de necessitats específiques dels professors. Al final del procés de refinament iteratiu, la percepció de la practicitat de la SEA i del seu enfocament didàctic innovador per part dels professors va ser molt positiva.

Situant-nos dins del paradigma de la recerca basada en el disseny, una interpretació acurada de la millora dels resultats dels alumnes a mesura que la SEA es va anar desenvolupant hauria de contemplar que aquesta innovació de qualitat és un resultat conjunt de la intervenció dissenyada i del context. En aquest sentit, cal mencionar que tots els canvis van ser consensuats entre els membres del grup de treball local basant-nos en les evidències obtingudes de manera que aquestes modificacions fossin decidides entre tots o, si més no, positivament rebudes pels professors que van participar en el disseny i en la implementació de la SEA a classe. El decreixement de les necessitats o dificultats dels professors de la primera a la segona implementació de la SEA pot ser interpretat com a resultat de la internalització dels objectius de cada activitat per part dels professors i de la gradual familiarització amb l'enfocament didàctic innovador i amb els materials d'aula. Per tant, les millores en els resultats dels alumnes no poden ser només atribuïdes al desenvolupament iteratiu de la SEA dissenyada sinó també a un creixent grau d'experiència i familiarització amb la SEA innovadora per part dels professors.

Tot i que existeix un gran consens sobre la importància de desenvolupar innovacions d'ensenyament i aprenentatge cíclicament des del camp de la didàctica de les ciències, el reconeixement del valor educatiu d'aquest procés no és extensiu entre els membres de la comunitat d'educadors de ciències i dissenyadors de materials didàctics. Tal com afirmà McDermott (2001, p. 1128), "els professors sovint jutgen l'èxit d'un nou curs o innovació en base a les seves impressions de quant han après els alumnes o com de satisfets semblen estar". Aquest no sembla ser un indicador o criteri vàlid per avaluar l'eficàcia d'una intervenció. En tot cas, aquestes percepcions no són fidedignes per tal de garantir la qualitat que s'espera d'una innovació educativa en un determinat context.

Finalment, destaquem que el seguiment o avaluació dels resultats dels alumnes a les activitats de classe, la interpretació de les dificultats i necessitats dels alumnes i dels professors, l'explicitació dels principis de disseny i l'alineament amb els mateixos i la identificació de punts febles o aspectes problemàtics de la SEA ha resultat ser una anàlisi útil i rica per contribuir al refinament de la SEA cap a la millora de la seva qualitat. En resum, el procés de desenvolupament iteratiu de la SEA sobre propietats acústiques dels materials ha estat productiu no només per millorar la qualitat de la SEA dissenyada i per donar suport als professors a l'hora d'adequar i implementar una SEA innovadora a les seves classes, sinó també pel coneixement sobre com refinar innovacions didàctiques que aquest llarg procés de recerca ha generat. Finalment, un altre resultat rellevant d'aquesta recerca és la pròpia SEA sobre propietats acústiques dels materials refinada i basada en resultats de recerca (Pintó *et al.*, 2009) que els professors poden utilitzar a les seves classes de ciències.

8.2. Sobre l'avaluació de l'eficàcia de seqüències d'ensenyament i aprenentatge i el desenvolupament de principis de disseny

Per tal de respondre a les dues últimes preguntes de recerca, cal que discutim els resultats descrits al manuscrit no publicat.

Quant a la *quarta pregunta de recerca*, descrivim a continuació els processos de desenvolupament dels models mentals dels alumnes cap als tres models conceptuals tractats al llarg de la SEA dissenyada.

En relació als estadis de desenvolupament d'aquests tres models conceptuals[7] per part dels alumnes, els nostres resultats mostren que:

- Al final de la implementació, més de la meitat dels alumnes va desenvolupar el model conceptual teòric del fenomen de l'atenuació del so en materials en termes de l'energia (CM1). La majoria dels alumnes va desenvolupar el model conceptual empíric del comportament acústic dels materials en termes de les seves propietats físiques (CM2). Aproximadament la meitat dels alumnes va arribar a desenvolupar el model conceptual teòric del comportament acústic dels materials en termes de la seva estructura interna (CM3), tot i que gairebé el 30% d'aquests l'utilitzaven juntament amb els seus models mentals inicials.
- La resta d'alumnes van progressar cap a estadis de desenvolupament intermedis entre els seus models mentals inicials i els models conceptuals esperats. Això significa que pràcticament la totalitat dels alumnes van experimentar algun tipus d'evolució des dels seus models mentals inicials a través de diversos estadis de desenvolupament, i

[7] Veure manuscrit no publicat a l'annex 2, on s'explica el significat atribuït a la terminologia "model conceptual teòric i model conceptual empíric".

alguns d'ells van arribar a desenvolupar els models conceptuals esperats.

En definitiva, el model conceptual CM2 va ser desenvolupat per un major nombre d'alumnes que el model conceptual CM1 i, alhora, aquest va desenvolupat per un major nombre d'alumnes que el model conceptual CM3.

Aquestes diferències d'assoliment dels diversos models conceptuals poden ser interpretades en termes dels atributs de cada model conceptual, en termes de la distància entre els models mentals inicials dels alumnes i els models conceptuals esperats, i/o en termes de la qualitat de la intervenció que va tenir lloc. En paraules de Duschl *et al.* (2011, p.152), "si els objectius d'aprenentatge són massa sofisticats o si la SEA no està ben concebuda, llavors els objectius d'aprenentatge esperats corren el risc de ser massa abstractes o d'estar fora dels 'límits' dels resultats d'aprenentatge esperats per uns determinats alumnes".

Tenint en compte els atributs de cada model i el punt de partida dels alumnes, podem dir que el model conceptual del comportament acústic dels materials en termes de les seves propietats físiques (CM2) és un model empíric que involucra entitats reals (o materials) i les seves propietats observables. Tenint en compte que els models mentals inicials dels alumnes sovint inclouen descripcions macroscòpiques d'objectes o esdeveniments naturals, que són fàcilment visibles o vinculats a la seva experiència quotidiana (Tiberghien *et al.*, 2009), considerem que en el cas d'aquest model conceptual (CM2) els models mentals inicials dels alumnes poden actuar com una intuïció productiva per la seva comprensió, que fàcilment pot esdevenir més sofisticada a través d'un ensenyament adequat. D'altra banda, els models conceptuals teòrics CM1 i CM3 consisteixen en descripcions d'esdeveniments no observables en termes d'entitats abstractes com l'energia i les partícules. Diversos estudis (per ex., Harrison i Treagust, 2002; Millar, 2005) han informat de la varietat de dificultats de comprensió dels alumnes sobre aquests conceptes. Les principals diferències entre el desenvolupament del model conceptual CM1 i CM3 poden ser explicades pel punt de partida dels alumnes. En el cas del model conceptual CM1, els models mentals inicials dels alumnes reflecteixen una visió intuïtiva del fenomen de l'atenuació del so en materials, que no és consistent amb el model conceptual esperat però que pot ser considerada una versió més simple del model conceptual esperat basada en magnituds mesurables (nivell d'intensitat sonora) que els alumnes poden relacionar fàcilment amb l'entitat abstracta de l'energia. En el cas del model conceptual CM3, els models mentals inicials dels alumnes ja inclouen entitats abstractes com les partícules però aquests models són incompatibles amb el model conceptual esperat ja que fan referència a models de so diferents (so com a entitat (Maurines, 1993; Hrepic, *et al.*, 2010) en comptes de so com a procés) i a models d'estructura de la matèria diferents (propietats relacionades amb la distància intermolecular vs propietats relacionades amb la massa de les partícules i la força dels enllaços entre partícules). Això explicaria l'alt percentatge d'alumnes que al final de la implementació de la SEA encara utilitzaven una versió híbrida del model CM3 (utilitzant alhora els seus models mentals inicials i el model conceptual esperat).

Una important implicació per a l'ensenyament i el disseny d'intervencions d'aula és que les progressions d'aprenentatge dels alumnes, expressades com estadis de desenvolupament gradualment més sofisticats dels models conceptuals, poden ajudar als professors a avaluar com progressen els alumnes a mesura que aprenen aquest contingut i a adaptar les seves intervencions en resposta a l'evolució i necessitats dels alumnes per tal de promoure el seu aprenentatge.

L'*última pregunta de recerca* d'aquest treball de tesi fa referència al paper de les activitats de la SEA en el desenvolupament dels models mentals dels alumnes cap als models conceptuals esperats.

Observant les progressions d'aprenentatge dels alumnes al llarg de les diverses activitats de la SEA, podem destacar el fet que diferents tipus d'activitats de modelització (Löhner *et al.*, 2005) semblen jugar un paper decisiu en el desenvolupament de cada model conceptual per part dels alumnes. En el cas del model teòric CM1, els nostres resultats semblen indicar que l'activitat que va facilitar més el desenvolupament dels models mentals dels alumnes és l'activitat de modelització exploratòria[8], a la qual s'introdueix la perspectiva científica als alumnes mitjançant un text i un diagrama als dossiers dels alumnes i es discuteix a classe, per tal que els alumnes puguin després revisar els seus models mentals comparant-los amb el punt de vista científic i utilitzar els seus models mentals revisats en tasques posteriors.

En el cas del model conceptual empíric CM2, l'activitat que sembla haver facilitat més el desenvolupament dels models mentals dels alumnes és l'activitat de modelització indagativa, a la qual els alumnes van realitzar un experiment i van obtenir evidències de les quals van extreure conclusions, en base a les quals els alumnes van revisar els seus models mentals. Altra activitat que també va tenir un impacte significatiu en el desenvolupament dels models mentals dels alumnes és l'activitat de modelització exploratòria, a la qual els alumnes van elaborar un model consensuat, després d'haver explicitat individualment els seus models mentals inicials i d'haver explorat nova terminologia i nous punts de vista.

Finalment, en el cas del model teòric CM3, l'activitat que aparentment va facilitar més el desenvolupament dels models mentals dels alumnes és l'activitat de modelització indagativa, a la qual els alumnes van realitzar un experiment mental tot utilitzant una analogia i van treure conclusions a partir de discutir-lo.

[8] Cal aclarir que no entenem les activitats de modelització exploratòries com activitats transmissives, a les quals el punt de vista científic o model conceptual esperat simplement és introduït pel professor o pel material. Amb aquest terme ens referim a activitats guiades a les quals els professors i els alumnes discuteixen i tracten d'apropar diferents perspectives i llenguatges.

Tenint en compte que els principis de disseny de la SEA contemplaven la integració de diversos tipus d'activitats de modelització, els resultats d'aquest estudi semblen apuntar cap a una idea més acurada del paper de cadascun d'aquests tipus d'activitats de modelització, destacades per Löhner *et al.* (2005), en el desenvolupament de models conceptuals per part dels alumnes. Segons aquests resultats, activitats de modelització exploratòries semblen tenir un paper més significatiu en el desenvolupament del model conceptual teòric CM1, mentre que activitats de modelització indagatives semblen haver tingut un major impacte en el desenvolupament del model conceptual empíric CM2 i del model conceptual teòric CM3.

El fet que les activitats de modelització exploratòries tinguin un impacte tant significatiu en el desenvolupament del model teòric CM1 podria suggerir que un enfocament didàctic purament indagatiu podria resultar poc efectiu per promoure el desenvolupament de models conceptuals teòrics, que defineixen entitats abstractes que no poden ser directament construïdes a partir dels resultats de cap activitat experimental. Altres autors (Viennot, 2010) també han demanat precaució a l'hora de proposar enfocaments didàctics purament indagatius, argumentant en termes similars.

De tota manera, no podem interpretar la influència de cada tipus d'activitat de modelització sense tenir en compte tant els atributs de cada model conceptual (teòric o empíric) així com les activitats que els alumnes havien realitzat anterior i posteriorment (per ex., explicitar els seus models mentals inicials, obtenir noves evidències empíriques i extreure conclusions a partir de les mateixes). Per aquest motiu, considerem important remarcar la importància d'incloure els diversos tipus d'activitats de modelització a l'hora de dissenyar una SEA i, en aquest sentit, advoquem per que qualsevol SEA parteixi de posar als alumnes en situació d'explicitar els seus propis models mentals inicials per tal de provocar la necessitat de revisar-los en base a noves evidències (empíriques o no) obtingudes a partir d'experiments reals o mentals o proporcionades, abans de procedir a introduir i discutir a classe el model conceptual esperat.

SECCIÓ IV. REFERÈNCIES BIBLIOGRÀFIQUES

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SECCIÓ V. ANNEXOS

Annex 1

Carta d'acceptació per a la presentació de la tesi com a compendi de publicacions

UAB Escola de Postgrau
Universitat Autònoma de Barcelona

Universitat Autònoma de Barcelona - Registre General Escola de Postgrau
Sortida
014 Num. 201200007741
17/05/12 10:24:54

Exp. ED

Sra. María Isabel Hernández Rodríguez
Santa Engràcia, 9, casa 6
08290 Cerdanyola del Vallès

Vista la instància presentada per en/na María Isabel Hernández Rodríguez de sol·licitud de presentació de tesi doctoral com a compendi de publicacions,

De conformitat amb el que disposa la Normativa acadèmica de la UAB aplicable als estudis universitaris regulats de conformitat amb el RD 1393/2007, de 29 d'octubre, modificat pel RD 861/2010, de 2 de juliol (text refós aprovat per l'Acord de Consell de Govern de 2 de març de 2011),

Atès que les publicacions que conformin una tesi per compendi de publicacions han hagut d'haver estat publicades o acceptades per a la seva publicació,

RESOLC

Acceptar la presentació de la tesi doctoral de María Isabel Hernández Rodríguez com a compendi de publicacions amb els articles següents:

- Hernández, M.I.; Couso, D.; Pintó, R. "The Analysis of Students' Conceptions as a Support for Designing a Teaching/Leraning Sequence on the Acoustic Properties of Materials". A: *Journal of Science Education and Technology* (2011).
- Hernández, M.I.; Couso, D.; Pintó, R. "Teaching acoustic properties of materials in secondary school: testing sound insulatros". A: Physics Education (2011: 46, 559-569).
- Hernández, M.I.; Pintó, R. "The Process of Iterativa Development of a Teaching/Learning Sequence on Acoustic Properties of Materials" A: Psillos, E. & Dariotoglou, P. *Iterative degign of teaching-learning sequences: introducing the science of materials in European schools* (acceptat per a publicació).

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Contra aquesta resolució, que no esgota la via administrativa, les persones interessades poden interposar recurs d'alçada davant la Rectora Magnífica de la UAB, en el termini d'un mes, a comptar des del dia següent a la recepció d'aquesta notificació o, si s'escau, des del dia següent de la seva publicació, de conformitat amb el que preveu l'article 115 de la Llei 30/1992, de 26 de novembre, de Règim Jurídic de les Administracions Públiques i del Procediment Administratiu Comú, modificada per la Llei 4/1999, de 13 de gener, i l'article 76 de la Llei 26/2010, de 3 d'agost, de Règim Jurídic i de Procediment de les Administracions Públiques de Catalunya de la Generalitat de Catalunya.

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La publicació següent podrà formar part de la tesi com a annex o part no fonamental, tot i que els treballs fets en aquesta publicació es poden comentar en la discussió de resultats.

- Hernández, M.I.; Couso, D.; Pintó, R. "Refining design principles of a teaching-learning sequence with a model-based inquiry apporach: Contributions from the analysis of studentes' learning pathways" (manuscrit).

La Comissió d'Estudis de Postgrau,
Per delegació

Escola de Postgrau
Doctorat

Jaume FARRÉS VICÉN
Delegat de la Rectora per al Doctorat

Bellaterra (Cerdanyola del Vallès), 16 de maig de 2012

Contra aquesta resolució, que no esgota la via administrativa, les persones interessades poden interposar recurs d'alçada davant la Rectora Magnífica de la UAB, en el termini d'un mes, a comptar des del dia següent a la recepció d'aquesta notificació o, si s'escau, des del dia següent de la seva publicació, de conformitat amb el que preveu l'article 115 de la Llei 30/1992, de 26 de novembre, de Règim Jurídic de les Administracions Públiques i del Procediment Administratiu Comú, modificada per la Llei 4/1999, de 13 de gener, i l'article 76 de la Llei 26/2010, de 3 d'agost, de Règim Jurídic i de Procediment de les Administracions Públiques de Catalunya de la Generalitat de Catalunya.

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Annex 2

Article no publicat

L'article no publicat consisteix en l'anàlisi del desenvolupament de models conceptuals per part de 29 alumnes de 4t d'ESO al llarg de diferents tasques realitzades al llarg i al final de la implementació de la versió refinada de la seqüència d'ensenyament i aprenentatge sobre propietats acústiques dels materials. Aquest article presenta els principis de disseny de la SEA que justifiquen l'estructura i els tipus d'activitats de modelització i indagació dissenyades per promoure el desenvolupament de tres models conceptuals consistents amb la perspectiva científica. Aquest procés de modelització s'ha guiat a través de plantejar la indagació com a estratègia mediadora en el procés de construcció de models per part dels alumnes.

En definitiva, l'anàlisi de les produccions escrites dels alumnes ens ha permès caracteritzar els processos de modelització dels alumnes i entendre millor la influència de determinades activitats de la SEA en aquests processos d'aprenentatge.

Aquest article dóna compte dels procediments i resultats de l'avaluació de la SEA sobre propietats acústiques dels materials, com a part de la recerca global sobre el desenvolupament iteratiu de la mateixa. A més, s'aborda el tema del desenvolupament de principis de disseny en el marc de la recerca basada en el disseny de la SEA.

Refining design principles of a teaching-learning sequence with a model-based inquiry approach: Contributions from the analysis of students' learning pathways

María Isabel Hernández, Digna Couso, Roser Pintó

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Abstract This study aims to characterize 15-16-year-old secondary school students' learning pathways throughout the implementation of a teaching-learning sequence on the acoustic properties of materials. Its purpose is to better understand the students' modelling processes and the design principles relating to the model-based inquiry approach of the teaching sequence. This article presents the design principles which elicit the structure and types of modelling and inquiry activities designed to promote students' development of three conceptual models. Framing this study within the design-based research paradigm, it consists of the experimentation of the designed teaching sequence with two groups of students (n = 29) in their science classes. The analysis of their productions in class allowed us to characterize the students' processes of construction of each of the intended conceptual models through several intermediate mental models that acted as 'stepping-stones'. Moreover, we could evidence the influence of the designed modelling and inquiry activities on students' development of conceptual models. Our results illustrate that the different types of conceptual models involve different learning demands, which can be interpreted by taking into account the attributes of each model and the distance between students' preliminary mental models and the intended conceptual models. Furthermore, we conclude that specific modelling activities (e.g. inquiry-modelling activities) have a greater impact on promoting students' development of certain types of conceptual models (e.g. empirical models). Further implications for design and for teaching are also described.

Keywords: model-based inquiry; design-based research; learning pathways; teaching-learning sequence; acoustic properties of materials; design principles

Introduction

This study aims to characterize 15-16-year-old secondary school students' learning pathways throughout the implementation of a teaching-learning sequence on the acoustic properties of materials (Pintó et al., 2009) with the purpose of better understanding the students' modelling processes and refining the design principles relating to the model-based inquiry approach of the teaching sequence. This teaching sequence is largely aimed at promoting students' development of three conceptual models: (1) sound attenuation in materials in terms of energy distribution (CM1); (2) the acoustic behaviour of materials in terms of their physical properties (CM2); and (3) the acoustic behaviour of materials in terms of their internal structure (CM3). We are especially interested in understanding the process of students' construction and use of the aforementioned conceptual models as a result of their engagement in the activities that are part of the designed teaching sequence. Consequently, from the analysis of students' learning pathways we intend to refine the design principles in order to provide research-based insights for teaching and learning the specific content that is tackled throughout the teaching sequence with a model-based inquiry approach.

Theoretical Framework

On models and modelling in science and science education

With the purpose of using a working definition of the term model throughout this article, we explain here our understanding of different terms such as scientific model, conceptual model, and mental model. As defined by Bunge (1973, cited in Gutiérrez & Pintó, 2005), a scientific model is a representation of a real or conjectured system, consisting of a set of objects with its outstanding properties listed, and a set of law statements that declare the behaviours of these objects. The essential functions of a scientific model are predictions and explanations. We distinguish between two types of scientific models: theoretical models and empirical models. A theoretical model is seen as a scientific model which defines idealized objects (Giere, 1999), whereas an empirical model (or 'model of data') is seen as a scientific model which describes patterns or regularities inferred from observable behaviours of real-world entities or systems (Koponen, 2007). By conceptual model we refer to a representation of physical objects, phenomena, or processes which is not contradictory to scientifically accepted knowledge and is shared by a given community (researchers, teachers, etc.) (Greca & Moreira, 2000). In science education, a conceptual model is seen as a scientific model that has been didactically transposed to facilitate the understanding of a specific group of students (Acher, Arcà, & Sanmartí, 2007; Buty, Tiberghien, & Le Maréchal, 2004). Norman (1983, cited in Glynn & Duit, 1995) emphasizes the distinction between conceptual models and mental models, understanding the latter as incomplete representations that correspond to what people really have in their heads and what guides their use of things. Literature has shown that students' mental models can be identical to, similar to, or quite different from the conceptual models that are intended to be taught in science class.

Currently, many authors in philosophy and the history of science and cognitive studies of science consider that the model-based views of scientific knowledge construction and of scientific reasoning are valid for depicting the practice of science (e.g. Giere, 1999; Nersessian, 1995, 1999). These model-based views state that the development of scientific knowledge consists of the progressive or cyclical construction, evaluation and revision of models. Given this model-based philosophical stance towards scientific knowledge development, science education researchers have highlighted the need to promote model-based approaches to teaching and learning science in schools (e.g. Clement, 2000; Gilbert & Boulter, 1998; Gobert & Buckley, 2000; Izquierdo-Aymerich & Adúriz-Bravo, 2003; Tiberghien, 1994). Thus, these pedagogical approaches are grounded on the idea that the particular practices which are integral to the core work of science, and which can consequently offer an authentic scientific experience to learners, are organized around the development of conceptual models explaining how the natural world works.

Model-based teaching approach and modelling-based teaching approach

The model-based teaching approach is a polysemic one in science education: some authors refer to it when talking about teaching and learning the knowledge content of scientifically accepted models; others focus on teaching modelling processes as a scientific practice. We consider that teaching and learning science as a modelling process (i.e. constructing and refining conceptual models) are essentially different from teaching and learning scientific models in the science classroom. This modelling-based teaching and learning approach (Louca, Zacharia, & Constantinou, 2011) is therefore focused on students' construction and refinement of conceptual models. Within this modelling perspective, Rea-Ramirez, Clement and Núñez-Oviedo (2008) suggest that a model-based teaching and learning approach in the science classroom should engage students in a modelling process that allows them to reflect on and progressively improve their own mental models through recurring cycles of generation, evaluation and modification, in order to accord with their own thinking and with the data obtained from the external world.

The Two Worlds framework described by Buty et al. (2004) also recognizes that modelling processes play a central part in understanding science by relating descriptions of objects and events in the material world to the world of theories and models. According to these authors, everyday knowledge and scientific knowledge offer ideas and languages for describing objects and events of the material world and these are linked via modelling processes. As stated by Tiberghien, 'the distinction between the world of theories/models and the world of objects/events serves to make explicit the modelling processes that establish relationships between them' (Ruthven, Laborde, Leach, & Tiberghien, 2009, p. 335).

Modelling activities in the science class

The model-based approach which emphasizes the modelling process can be put into practice through different modelling activities. Authors such as Mellar and Bliss (1994) have described different modelling activities for teaching and learning science which, according to them, reflect how scientists construct and/or use scientific models in their work to study the natural world. These authors distinguish between two types of modelling activities: exploratory modelling, in which students investigate the properties of models which are explicitly or implicitly introduced; and expressive modelling, in which students create models to express their own conceptions about particular targets (phenomena, events, mechanisms). We also highlight the contribution made by Löhner, van Joolingen, Savelsbergh and van Hout-Wolters (2005), who add one type of modelling activity to the two aforementioned activities: inquiry modelling, in which students construct models that allow them to interpret and to predict outcomes from experimenting with phenomena.

Looking in more detail at the previous perspective, Schwarz et al. (2009) evidence that the model-based teaching approach includes common activities such as: exploring phenomena that may necessitate using a model to figure it out, constructing a model, empirically or conceptually testing the model, evaluating the model, revising the model, and using the model to explain and predict.

Model-based inquiry approach

Within the literature devoted to modelling processes in science education, we can find some authors (e.g. Justi & Gilbert, 2002) who include certain inquiry practices (e.g. designing and performing experiments) as part of the modelling process that students carry out in the science class. This has led some authors (Khan, 2007; Lehrer, Schauble, & Lucas, 2008; Stewart, Cartier, & Passmore, 2005; Wells, Hestenes, & Swackhamer, 1995; Windschitl, Thompson, & Braaten, 2008) to link modelling and inquiry as two related teaching approaches that share common activities. This integrated teaching approach is usually called the model-based inquiry approach.

One argument for incorporating this approach in teaching science is put by Buckley (2000), who highlights that students' mental models are not only a source of comprehension but also a source of new questions. She argues that students' evaluation of their own mental models leads them to generate new questions which sustain them in an inquiry cycle of question generation, investigation, and model revision. In line with this, Schwarz and Gwekwerere (2007) propose an instructional framework based on modelling and inquiry activities called EIMA, standing for Engage-Investigate-Model-Apply. These authors state that one of the major tasks of inquiry-based learning is to explore phenomena and construct and reconstruct models in the light of the results of inquiry activities. According to this, a model-based inquiry approach in the science class would include modelling activities together with inquiry activities, such as generating questions, designing experiments, collecting data, drawing conclusions, and communicating findings (Barrow, 2006; Minner, Levy, & Century, 2010).

Despite the above considerations, we are aware that, as stated by Chinn and Malhotra (2002), modelling-based and inquiry-based teaching could also become epistemologically non-authentic approaches. In particular, many scientific inquiry tasks given to students in schools do not reflect the core attributes of authentic scientific reasoning. Simple inquiry tasks may not only fail to help students learn to reason scientifically but they may also foster a view of scientific reasoning as simple, certain, algorithmic, and focused at a surface level of observation, and science may be viewed as a process of accumulating simple facts about the world. The same could be said of some model-based approaches, which only aim at teaching the knowledge content of scientifically accepted models but not the process of developing them. In sum, our educational goal is to develop integrated inquiry and modelling school activities that, despite their simplicity, capture core components of scientific reasoning (Viennot, 2010).

These contributions were taken into account when we designed and experimented with a teaching-learning sequence on the acoustic properties of materials.

On the design principles of a teaching-learning sequence

It is widely agreed that the application of grand learning theories like constructivism cannot guarantee that the teaching-learning sequences (TLS) that are derived from them have the necessary didactical quality (Lijnse & Klaassen, 2004; Tiberghien, Vince, & Gaidioz, 2009). In the words of diSessa (2006), these grand theories are too general and ambiguous and are considered ineffective in design-level decisions as 'they do not tell what to do or how to adjust something that is not quite working'.

Framing our research within the design-based research paradigm[1] (DBR), we do not focus on analysing grand theories but certain principles or specific theories (Andersson & Bach, 2005; Design-Based Research Collective, 2003; Tiberghien et al., 2009) applied in the design of the TLS, which help to refine our understanding of how the designed teaching sequence works in an authentic context. We consider that relating students' learning outcomes to specific features of the designed TLS should be an essential aspect of our research as specific instruction factors help students progress from lower to higher levels of understanding. In this context, as Duschl, Maeng and Sezen (2011) observe, details about the instructional interventions that might influence how students progress are often missing in published research studies of students' learning.

In order to refine the specific design principles guiding the model-based inquiry approach of a TLS, a possible procedure consists of exploring students' learning pathways[2] throughout the teaching sequence. Tracking students' cognitive pathways all through the teaching-learning process of specific teaching-learning interventions has gained prominence in science education over the last decades as many scholars agree that learning ought to be coordinated and sequenced along learning pathways (Driver, Leach, Scott, &

Wood-Robinson, 1994; Duschl et al., 2011; Niedderer & Goldberg, 1995; Schwarz et al., 2009; Scott, 1991; Talanquer, 2009; Viennot & Rainson, 1999). These learning pathways are generally viewed by researchers as conjectural or hypothetical model pathways of learning over periods of time that need to be empirically validated in the light of research on students' progress (Duschl et al., 2011).

How is this theoretical framework applied to the design of the teaching-learning sequence on acoustic properties of materials?

Taking into account the model of educational reconstruction (Duit, Gropengießer, & Kattmann, 2005), the design of the TLS on acoustic properties of materials (APM) involved several stages addressing critical analysis of the subject matter to be taught (Hernández, Couso, & Pintó, 2011a) and the students' conceptions of the nature, propagation and attenuation of sound and of the acoustic properties of materials (Hernández, Couso, & Pintó, 2011b).

Drawing on the ideas of Schwarz et al. (2009), we propose a common structure of each sequence of tasks designed to contribute to students' development of each intended conceptual model which includes the following modelling activities:

(1) elicitation of a preliminary mental model,

(2) revision of the mental model in agreement with new evidence obtained in hands-on or thought experiments,

(3) revision of the mental model in agreement with the scientific perspective,

(4) use/application of the revised mental model in a new context/task.

These modelling activities are carried out in several tasks, which correspond to exploratory modelling activities, expressive modelling activities, and inquiry modelling activities.

In each of these stages, several inquiry activities (e.g. reflecting on scientifically-oriented questions, designing experiments, collecting data, drawing conclusions, and communicating findings) are included in order to support the modelling activities described above.

The above-described structure of each sequence of tasks and the characteristics of the designed modelling and inquiry activities are our principles of design for the TLS on APM. Tables 1, 2, and 3 show how these design principles are applied throughout the teaching sequence and how modelling and inquiry activities are integrated.

Below, we describe the main features of the sequence of tasks included in the TLS on APM intended to contribute to students' construction and use of three conceptual models: (1) a theoretical model of the phenomenon of sound attenuation in materials in terms of energy (CM1); (2) an empirical model of the acoustic behaviour of materials in terms of their physical properties (CM2); and (3) a theoretical model of the acoustic behaviour of materials in terms of their internal structure (CM3).

Table 1 summarizes the sequence of tasks intended to contribute to students' development of the conceptual model of sound attenuation in materials (CM1), which allows them to:

- explain how sound attenuation is produced in materials in terms of energy distribution (energy of incident sound, energy of reflected sound, energy of transmitted sound and absorbed energy), and
- predict the acoustic behaviour of materials (sound reflector or sound absorber) in terms of the intensity level that is measured inside a closed space which has been covered with sound-attenuating materials.

Table 1. Description of the tasks and associated scientific practices intended to promote students' development of CM1.

TASKS	STRUCTURE OF THE SEQUENCE	SCIENTIFIC PRACTICES	
		MODELLING ACTIVITIES	INQUIRY ACTIVITIES
T1.1.1) Students are engaged in solving the problems of a disco that needs to be soundproof **T1.1.2)** Students are asked about sound transmission and sound attenuation in the disco in order to elicit their preliminary	Elicitation of a preliminary mental model to explain the phenomenon of sound attenuation in materials	Expressive modelling	Scientifically-oriented questioning

models of sound attenuation in materials			
T1.3.3) Students perform an experiment using a sound level meter and a sound source in order to investigate the empirical relationship between the intensity level of sound propagating through air and the distance between the sound source and the sound level meter **T1.3.4)** Students are placed in the situation of the owner of the disco, who has contracted an engineer to take measurements of the intensity level of the sound emitted inside the disco and of the sound transmitted to the neighbouring houses. Students have to calculate the attenuated sound taking into account the values corresponding to the measurements taken by the engineer **T1.3.5)** Students are asked to interpret how sound is attenuated in its path from the disco to the neighbouring houses	Revision of the mental model to be in agreement with new evidence obtained in a hands-on experiment	Inquiry modelling Expressive modelling	Scientifically-oriented questioning Collecting data Drawing conclusions from collected and provided data
What does science tell us? Students are engaged in discussing with their teacher and their classmates how science explains the process of sound attenuation when sound propagating through air interacts with a solid material. The scientific perspective is introduced by means of a written text and a visual representation[3] in their worksheets **T1.3.6 ,T1.3.7 & T1.3.9)** Students are asked to use the scientific perspective to interpret the acoustic behaviour of different materials, to design an experiment to test the capacity for attenuating sound of materials, and to elaborate solutions for the soundproofing problems of the disco	Revision of the mental model to be in agreement with the scientific perspective	Exploratory modelling Expressive modelling	Scientifically-oriented questioning Designing experiments Collecting data
Students apply their models to novel situations posed in later tasks and in the final assessment (**Q2, Q4.c & Q5.b**)	Use of the revised mental model to explain the attenuation of sound and the acoustic behaviour of materials	Expressive modelling	Scientifically-oriented questioning Designing experiments Collecting data Communicating findings

Table 2 summarizes the sequence of tasks intended to contribute to students' development of the conceptual model of the acoustic behaviour of materials in terms of their physical properties (CM2), which allows them to:

- explain how sound attenuating materials behave in front of sound, taking into account their (acoustic) physical properties (density, rigidity and porosity), and

- predict the acoustic behaviour of materials in terms of their acoustic physical properties (i.e. sound reflectors have high density, high rigidity and no porosity, whereas sound absorbers have low density, low rigidity and porosity).

Table 2. Description of the tasks and associated scientific practices intended to promote students' development of CM2.

TASKS	STRUCTURE OF THE SEQUENCE	SCIENTIFIC PRACTICES	
		MODELLING ACTIVITIES	INQUIRY ACTIVITIES
Students are engaged in the process of solving the soundproofing problem of the disco by selecting appropriate materials **T2.1.1)** Open-ended question in which students elicit their prior ideas on the properties that affect the acoustic behaviour of materials **T2.1.2)** Closed question in which students elicit their prior ideas on the properties that affect the acoustic behaviour of materials. This activity introduces new terminology and new perspectives that students discuss with their classmates. At the end, students reach a consensus model of the acoustic behaviour of materials in terms of their properties **T2.1.3)** Students apply their consensus model to predict the acoustic behaviour of certain materials	Elicitation of a preliminary mental model to explain the acoustic behaviour of materials in terms of their properties	Expressive modelling Exploratory modelling	Scientifically-oriented questioning Making predictions
T2.1.4 & T2.1.5) Students investigate the influence of certain properties on the acoustic behaviour of different materials by designing and carrying out an experiment that allows testing of the previous predictions **T2.1.6)** In the light of the results of the experiment, students classify the tested materials in sound reflectors and sound absorbers. Then, students observe and manipulate these materials and describe the properties that the materials from each group have in common with the materials from the same group	Revision of the mental model to be in agreement with new evidence obtained in a hands-on experiment	Inquiry modelling Expressive modelling	Scientifically-oriented questioning Designing an experiment Collecting data Drawing conclusions from collected data
T2.1.7 & T2.1.8) Students are engaged in discussing the scientific meaning of the so-called acoustic properties of materials and subsequently analyse more accurate data of certain properties of the tested materials	Revision of the mental model to be in agreement with new evidence and more accurate definitions of properties	Exploratory modelling Inquiry modelling Expressive modelling	Scientifically-oriented questioning Drawing conclusions from provided data and observations
Students apply their models to novel situations posed in later tasks and in the final assessment (**Q4.a & Q5.a**)	Use of the revised mental model to explain and predict the acoustic behaviour of materials in terms of their properties	Expressive modelling	Scientifically-oriented questioning Collecting data Drawing conclusions from collected data Communicating findings

Table 3 summarizes the sequence of tasks intended to contribute to students' development of the conceptual model of the acoustic behaviour of materials in terms of their internal structure (CM3), which allows them to:

- explain the mechanisms of sound attenuation in materials using the particulate model of matter in terms of more or less vibration of the particles that form each material, and
- relate the acoustic behaviour of materials to the mass and arrangement of their particles and the strength of their bonds.

Table 3. Description of the tasks and associated scientific practices intended to promote students' development of CM3.

TASKS	STRUCTURE OF THE SEQUENCE	SCIENTIFIC PRACTICES	
		MODELLING ACTIVITIES	INQUIRY ACTIVITIES
Students are engaged in the process of solving the soundproofing problem of the disco by selecting appropriate materials **T2.1.1)** Open-ended question in which students elicit their prior ideas on the properties that affect the acoustic behaviour of materials **T2.1.2)** Closed question in which students elicit their prior ideas on how the internal structure of materials affects their acoustic behaviour. This activity introduces new terminology and new perspectives that students discuss with their classmates	Elicitation of a preliminary mental model to explain the acoustic behaviour of materials in terms of their internal structure	Expressive modelling	Scientifically-oriented questioning
T2.2.1, T2.2.2, T2.2.3, T2.2.4 & T2.2.5) Students investigate the influence of the internal structure of materials on their acoustic behaviour in terms of the ball-and-spring model and an analogy.[4] Students are then expected to transfer the language and reasoning used with the analogy to explain how density, rigidity and porosity of materials can be conceptualized at the level of their internal structure and how these properties affect their acoustic behaviour	Revision of the mental model to be in agreement with new evidence obtained in a thought experiment	Inquiry modelling Expressive modelling	Scientifically-oriented questioning Thought experiment Drawing conclusions
What does science tell us? Students discuss with their teacher and their classmates the scientific view on how the properties of sound absorbers affect their acoustic behaviour **T2.2.6 & T2.2.7**) Students use the same line of reasoning to explain how the properties of certain materials affect their acoustic behaviour	Revision of the mental model to be in agreement with the scientific perspective	Exploratory modelling Expressive modelling	Scientifically-oriented questioning

Students apply their revised mental models to novel situations posed in the final assessment (**Q5.b**)	Use of the revised mental model to explain the acoustic behaviour of materials in terms of their internal structure	Expressive modelling	Scientifically-oriented questioning

Research Questions

We agree with Anderson (2002) that research on teaching approaches has matured enough to be focused more on understanding the dynamics of learning and how it can be brought about. As stated by Louca et al. (2011), crucial information is still missing in published research studies regarding the process that students follow when implementing a model-based teaching and learning approach.

Taking into account the gaps identified above, this study will devote particular attention to experimenting with the designed teaching sequence in order to explain: (1) the dynamics of students' development of conceptual models on sound attenuation and the acoustic properties of materials throughout the implementation of the designed teaching sequence; and (2) the influence of the design principles of the teaching sequence, related to the model-based inquiry approach, on students' learning pathways. In particular, we will try to answer the following research questions:

(1) How do students progress from their preliminary mental models of sound attenuation in materials and of the acoustic behaviour of materials towards the intended conceptual models throughout the implementation of the teaching-learning sequence?

(2) What are the salient modelling and inquiry activities of the designed teaching-learning sequence that contribute more to the students' development of the intended conceptual models?

The answer to the latter question will help us to refine the principles that guided the design of the model-based inquiry approach of our TLS on APM.

Methodology of Research

Context of Research

The research presented here was carried out within the context of the implementation of the designed TLS on APM. The design and iterative development of this TLS (Hernández & Pintó, in press) was carried out during three consecutive years (2007 to 2009) by three researchers in science education and six experienced secondary school teachers (one physics graduate and five chemistry graduates) from four different schools. The main reasons for opting for a strong university-school collaboration for the development of the sequence were the emphasis on a participatory view of curriculum design (Couso, in press) to promote learning on the part of all the members and the intention to avoid critical transformations (Pintó, 2005; Viennot, Chauvet, Colin, & Rebmann, 2005) of the innovation when it was implemented.

The designed TLS on APM was planned to be implemented in ordinary schools with tenth-graders (15-16-year-old students) within the science subject 'physics and chemistry'. In the Spanish educational context the tenth grade is the last compulsory academic year for students under 16 years old and it is also the first grade in which the study of physics and chemistry is optional. The official science syllabus for the last year of compulsory secondary school, which suggests a qualitative and phenomenological study of the contents, includes the following main topics: sound waves, and the structure and properties of matter, among other topics. Most of the aforementioned topics were studied before the implementation of the innovative sequence on APM as prerequisites for it.

Regarding the teaching strategies, although all the teachers in our context are used to encouraging students to work in groups to a greater or lesser extent, most of them were interested in developing more pedagogical resources related to the model-based inquiry approach of the TLS. As these teachers implemented the consecutive refined versions of the teaching sequence, its teaching approach and associated teaching strategies did not present a major challenge to them when implementing the third (and most refined) version of the TLS.

The conditions under which the sequence was implemented and the research data were collected correspond to the ordinary context of these teachers' science classes. As not all the teachers involved in the design could implement the last version (resulting from several refinements) of the designed teaching sequence at the same academic level, for the purposes of the research presented here we reduced our sample to 29 secondary school students (15-16-year-olds), who belong to two different class groups. The two teachers who could implement the whole sequence at this academic level devoted a similar number of hours (12 to 15) and followed the written teaching and learning material as it was structured. Both of them tended towards collaborative work and active discussion among their students. Table 4 presents a general description of each of the schools to which these class groups belong as well as the number of students who constitute our sample:

Table 4. General description of the sample.

School	Description of the school	Number of students
A	State secondary school in an urban area Medium-high socio-economic background of students Low number of immigrant students Low number of gifted students and those with special educational needs	12
B	Privately-run school funded by the state in a small town Medium-high socio-economic background of students Low number of immigrant students Low number of gifted students and those with special educational needs	17
A & B	**TOTAL SAMPLE**	**29**

Data collection

The present study is framed within the design-based research (DBR) paradigm, and so we used a range of mixed methods and techniques to collect data from students and to analyse the students' outcomes and the design principles of the TLS. With the purpose of analysing students' development of conceptual models, different learning and assessment tasks were collected. These tasks are domain-specific (i.e. specific to the content being taught and the goals), and so specific instruments had to be developed for collecting data in the domain of acoustic properties of materials. The collected data correspond to students' written answers to several tasks, included in the worksheets that students completed during the implementation of the sequence, and to students' responses to several questions, included in the final assessment. Table 5 specifies the tasks embedded in the TLS that were used to collect evidence on the development of each of the three conceptual models.

Table 5. Tasks and questions to collect evidence of students' development of each conceptual model.

Conceptual model	**Tasks and questions to collect evidence**			
	Elicitation of preliminary models	**Revision of the mental model to be in agreement with new evidence obtained in hands-on or thought experiments**	**Revision of the mental model to be in agreement with the scientific perspective**	**Use of revised models**
CM1	T1.1.2.a & T1.1.2.c	T1.3.5	T1.3.6 & T1.3.7 & T1.3.9	Q2 & Q4.c & Q5.b
CM2	T2.1.1 & T2.1.2.c & T2.1.3	T2.1.6.b	T2.1.8	Q4.a & Q5.a
CM3	T2.1.1 & T2.1.2	T2.2.2 & T2.2.4 & T2.2.5	T2.2.6 & T2.2.7	Q5.b

T refers to tasks included in students' worksheets and carried out throughout the implementation of the TLS. Q refers to questions posed in the written final assessment. The description of these tasks and questions can be found in Tables 1 to 3 and their statements are included in the Appendix.

Data Analysis

This study used an interpretative qualitative approach to answer the aforementioned research questions.

Before any implementation took place, each conceptual model that was intended to be developed by students throughout the teaching sequence was expressed in terms of a set of learning targets (LT). Each set of learning targets is therefore an expression of a conceptual model in a very specific and observable format. Table 6 shows the list of learning targets associated with each conceptual model to be developed by the students throughout the implementation of the teaching sequence.

Table 6. Intended learning targets associated with each conceptual model.

LT#	Description of each learning target associated with CM1
LT1	To recognize that sound is distributed in different parts when reaching an object
LT2	To recognize that part of the sound is reflected
LT3	To recognize that part of the sound is absorbed
LT4	To identify both reflection and absorption as mechanisms of sound attenuation
LT5	To (qualitatively and/or quantitatively) associate sound attenuation with the decrease in the intensity level of the incident sound when it is transmitted
LT6	To explain/interpret that sound attenuation involves energy changes/distribution
LT#	**Description of each learning target associated with CM2**
LT1	To identify properties related to density (density, compactness) of materials as one of the properties that influence the acoustic behaviour of materials
LT2	To identify properties related to rigidity (hardness, elasticity) of materials as one of the properties that influence the acoustic behaviour of materials
LT3	To identify porosity as one of the properties that influence the acoustic behaviour of materials
LT4	To relate density appropriately to the acoustic behaviour of materials (the more dense they are, the more sound reflects)
LT5	To relate rigidity appropriately to the acoustic behaviour of materials
LT6	To relate porosity appropriately to the acoustic behaviour of materials
LT7	To explain the acoustic behaviour of materials uniquely in terms of their density, rigidity and porosity and relate them appropriately to the acoustic behaviour of materials
LT#	**Description of each learning target associated with CM3**
LT1	To relate the acoustic behaviour of materials to the internal structure of materials
LT2	To describe density, rigidity and porosity of materials in terms of their microstructure
LT3	To use the particulate model of matter to explain mechanisms of sound attenuation in materials
LT4	To describe density, rigidity or porosity of materials appropriately in terms of their microstructure
LT5	To use the particulate model of matter appropriately to explain mechanisms of sound attenuation in materials

After the implementation of the last version of the TLS, we proceeded to analyse students' achievement of each learning target at different stages of the implementation with a twofold aim: (1) to evaluate the degree of students' achievement of each learning target at the end of the implementation compared with their starting point, and (2) to evidence the learning targets that are more easily achieved by students at each stage of the implementation.

As each conceptual model had been expressed in terms of a set of learning targets, we grouped the learning targets that students achieved at each phase of the implementation of the teaching sequence in order to characterize the evolution of students' mental models towards the intended conceptual models. Thus, we expected to describe several stages of progress (Corcoran, Mosher, & Rogat, 2009, p.15), which would characterize significant intermediate steps or stepping-stones in the development of increasingly elaborate mental models. These stepping-stones allowed students to move from 'lower anchors', which represent the knowledge students bring with them to school, towards 'upper anchors', which represent our expectations of what students should know and be able to do at the end of the instruction. Thus, we could characterize what students' mental models looked like at each stage, and also the percentage of students who would hold each mental model at each stage of the implementation. In this sense, the analysis would allow us to infer a bottom-up learning pathway that describes students' development of each conceptual model. That is to say, the learning pathway is grounded in assessments that obtain evidence of student learning and build on it, instead of simply being based on a logical task analysis of content domains and personal experiences with teaching (Duschl et al., 2011). This procedure would allow us to evidence the influence of each activity of the designed TLS on students' development of the three conceptual models described above.

Finally, with the purpose of validating the bottom-up students' learning pathways towards the construction of each conceptual model, we tracked each student's pathway, to illustrate whether the students experienced progression, regression or no evolution at all as a result of their engagement in each activity of the TLS.

The whole procedure of analysis described above was carried out for each conceptual model in order to draw specific conclusions on the influence of the modelling and inquiry activities included in the TLS on the students' development of each type of conceptual model.

Results

Students' development of the theoretical conceptual model of sound attenuation in materials in terms of energy (CM1)

As described earlier, the analysis of the students' development of each conceptual model took into account the results of a preliminary analysis, which consisted of exploring students' achievement of specific learning targets and characterizing students' models in terms of their learning outcomes.

Students' achievement of each learning target associated with the conceptual model of sound attenuation in materials in terms of energy (CM1)

The findings of the analysis of students' achievement of learning targets associated with the conceptual model of sound attenuation in materials in terms of energy (CM1) are illustrated in Table 7.

Table 7. Learning targets related to students' development of the CM1.

LT - CM1	T1.1.2.a & T1.1.2.c	T1.3.5	T1.3.6 & T1.3.7 & T1.3.9	Q2 & Q4.c & Q5.b
LT1	96%	75%	95%	93%
LT2	92%	58%	95%	93%
LT3	23%	42%	95%	89%
LT4	19%	25%	95%	86%
LT5	62%	-*	89%	82%
LT6	12%	0%	68%	68%

* It was not possible to track the students' achievement of this specific learning target in this activity.

As shown in Table 7, at the beginning of the implementation of the teaching sequence (T1.1.2.a and T1.1.2.c) more than 90% of students were already able to recognize that sound is distributed in different components when reaching an object such as a wall (LT1). Nevertheless, most students only identified transmitted sound and reflected sound as the components in which incident sound is distributed (LT2). Only 23% of students identified absorption as a mechanism of sound attenuation (LT3). Although almost two-thirds of the students already associated sound attenuation in materials with the decrease in the intensity level of the incident sound when it is transmitted through a material (LT5), only 12% of students associated sound attenuation with the distribution of energy (LT6).

The analysis of students' responses to the intermediate task T1.3.5 indicated that the number of students who recognized absorption within the medium as a possible mechanism of sound attenuation (LT3) increased (42%), whereas the percentage of students who identified reflection decreased (58%). Nevertheless, these results also illustrate that most students (75%) were not able to identify both reflection and absorption as mechanisms of sound attenuation (LT4) and none of them interpreted sound attenuation produced through a material in terms of energy distribution (LT6).

After T1.3.5 students were faced with a text and a visual representation that (verbally and diagrammatically) showed how science explains the process of sound attenuation when sound propagating through air interacts with a solid material. After discussing the text and the visual representation with their teacher and peers, students proceeded to perform other tasks (T1.3.6, T1.3.7 and T1.3.9). The answers to these tasks give evidence of an increase of up to about 90% of students who were able to identify both reflection and absorption as mechanisms of sound attenuation (LT4) and to associate sound attenuation appropriately with the decrease in the intensity level of the incident sound when transmitted (LT5). Moreover, the analysis of students' responses also illustrated that more than two-thirds of students (68%) were able to explain or interpret that sound attenuation involves distribution of energy (LT6).

Finally, the questions posed in the final assessment reveal similar levels of students' achievement of the learning targets associated with CM1. At that point, about 90% of students were able to identify both reflection and absorption as mechanisms of sound attenuation (LT4), about 80% of students were able to associate sound attenuation appropriately with the decrease in the intensity level of the incident sound when transmitted (LT5) and almost 70% of students were able to explain or interpret that sound attenuation involves distribution of energy (LT6).

Students' stages of development of the conceptual model of sound attenuation in materials in terms of energy (CM1) at each phase of the TLS

After carrying out the previous analysis, we grouped the subsets of learning targets that most students achieve at each phase of the implementation of the teaching sequence. Accordingly, we characterized four common students' mental models that correspond to progressively more elaborate mental models of sound attenuation in materials. Table 8 presents the empirically-based description of the stages of development of this conceptual model and also includes students' answers to illustrate the evolution of CM1.

Table 8. Description of the stages of development of CM1 and students' answers.

Stage of development of CM1	Description of students' models	Students' answers
S1	Students explain sound attenuation in a material as the decrease in sound intensity level resulting from the distribution of sound in different components such as transmitted sound and reflected sound – LT1, LT2 & LT5	**T1.1.2.a**) *"[When sound emitted by loudspeakers reaches the walls of a disco] it bounces back and a some goes outside the disco through the wall"* (S20)
S2	Students explain sound attenuation in a material as the decrease in sound intensity level resulting from the distribution of sound in different components such as transmitted sound and absorbed sound – LT1, LT3 & LT5	**T1.3.5**) [The part of sound that is not transmitted through the walls] has been absorbed by the walls (S18)
S3	Students explain sound attenuation in a material as the decrease in sound intensity level resulting from the distribution of sound in different components such as transmitted sound, reflected sound and absorbed sound – LT1, LT4 & LT5	**T1.3.5**) [The part of sound that is not transmitted through the walls] has been reflected or absorbed by the walls (S20)
S4	Students explain sound attenuation in a material as the decrease in sound intensity level resulting from the distribution of energy of sound in different components such as the energy of transmitted sound, the energy of reflected sound and the absorbed energy– LT1, LT4, LT5 & LT6	**T1.3.9**) To increase sound attenuation in the neighbours' house, the energy and the intensity of sound must be decreased. To do so, the walls need to be good sound absorbers and insulators so that absorption and reflection of sound are higher (S20)

After characterizing each stage of development of CM1, we analysed the distribution of students in each stage of development of CM1 throughout the implementation of the teaching sequence. This distribution is represented in Figure 1.

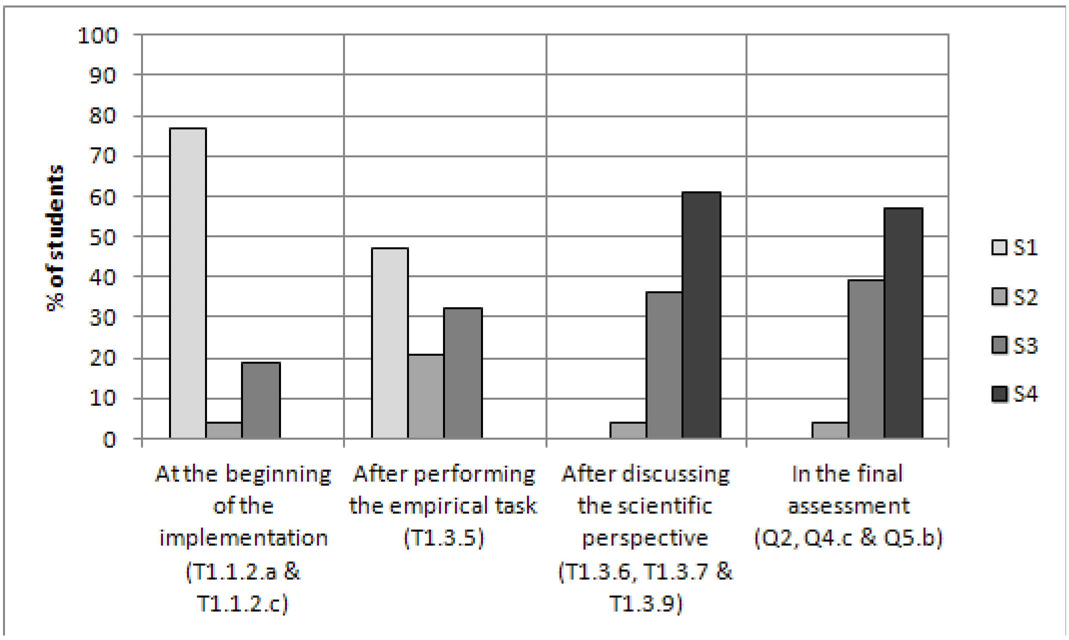

Figure 1. Students' development of CM1 throughout the implementation of the TLS.

In Figure 1, we can see that at the beginning of the implementation of the teaching sequence, most students (77%) elicited a mental model that explains sound attenuation in materials as the decrease in the intensity level of incident sound (LT5) resulting from the distribution of sound in different components (LT1) such as transmitted sound and reflected sound (LT2). We consider this students' preliminary model as the first stage (S1) or starting-point in the process of development of CM1.

After the experiment (T1.3.3) in which students measured the effects of distance on sound intensity level, students' worksheets included some data corresponding to measurements of incident and transmitted sound inside and outside a house (T1.3.4). Analysing students' answers to T1.3.5, in which they interpreted how sound is attenuated, some progression could be noticed as a higher number of students seemed to hold a conceptual model that recognizes absorption as a mechanism of sound attenuation (S2 or S3). These results suggest that the experiment that students performed contributed to the revision of their mental models to fit the new empirical evidence.

In spite of this progression of students' mental models of sound attenuation in materials, our results also illustrate that most of their mental models (47%) still belong to the first stage (S1) of development of CM1. Therefore, these results also emphasize the need for further activities to contribute to students' learning progression towards the construction of CM1. In this context, after students had expressed and revised their preliminary mental models in the exercise on interpreting the phenomenon of sound attenuation, they were introduced to the scientific perspective and discussed it with their teacher and classmates. This activity seemed to have a strong positive effect in terms of promoting the revision of students' mental models as our results indicate that most of the students (60% approximately) reached the fourth stage (S4) of the learning progression, that is to say the most elaborate version of the conceptual model of sound attenuation in materials.

Finally, the questions posed in the final assessment reveal that almost 40% of students seemed to hold a conceptual model of sound attenuation which corresponds to the third stage of development (S3) of CM1, whereas most of the students (about 60%) were found to have been able to develop the more elaborate version of the conceptual model of sound attenuation (S4) at the end of the teaching sequence.

Influence of the activities of the TLS on students' learning pathways towards the construction of the conceptual model of sound attenuation in materials in terms of energy (CM1)

With the purpose of validating the students' learning pathways towards the construction of CM1, we tracked each student's pathway throughout the TLS. Table 9 shows the types of evolution experienced by students while developing their model of sound attenuation in materials.

Table 9. Types of learning pathways experienced by students while developing CM1.

Type of evolution of students' models	Before and after the empirical task	Before and after discussing the scientific perspective	Before and after applying the model in later tasks
Progression	29%	**84%**	26%
Regression	18%	5%	26%
No evolution	**53%**	11%	**48%**

In general terms, these results highlight that the activities that students carried out to obtain new evidence from a hands-on experiment and to draw conclusions from it, and also the students' use of their revised models before the final assessment, promoted slight learning progress (29% and 26% respectively). In contrast, the activity that had a greater impact on students' development of CM1 (84%) was their engagement in the discussion of the scientific perspective on sound attenuation in materials, which was introduced to students by means of a written text (i.e. 'What does science tell us?'. See Table 1) about how science interprets this phenomenon and a diagram showing how the energy of the incident sound is distributed when sound reaches an object.

To sum up, Figure 2 represents the most common learning pathway towards the construction of the conceptual model of sound attenuation in materials throughout the implementation of the TLS.

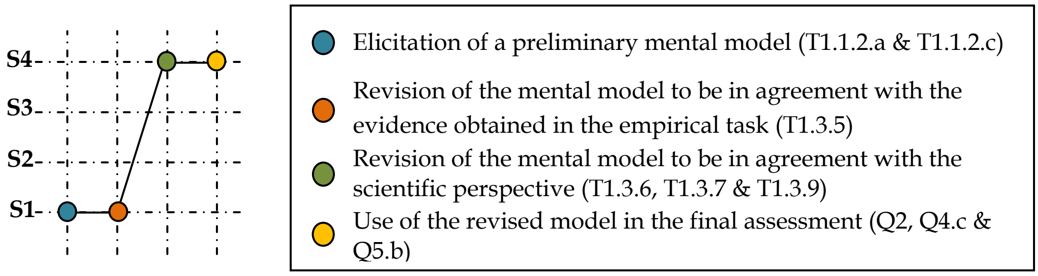

Figure 2. Description of the process of students' development of CM1 throughout the implementation of the TLS.

Students' development of the empirical conceptual model of the acoustic behaviour of materials in terms of their physical properties (CM2)

Students' achievement of each learning target associated with the conceptual model of the acoustic behaviour of materials in terms of their physical properties (CM2)

As described previously, CM2 is another key conceptual model that students were expected to develop throughout the designed TLS in order to explain and predict the acoustic behaviour of materials regarding their capacity for attenuating sound. The findings of the analysis of students' achievement of learning targets associated with the conceptual model of the acoustic behaviour of materials in terms of their properties (CM2) are illustrated in Table 10.

Table 10. Learning targets related to students' development of CM2.

LT – CM2	T2.1.1	T2.1.2.c	T2.1.3	T2.1.6.b	T2.1.8	Q4.a	Q5.a
LT1	68%	83%	86%	95%	-	100%	96%
LT2	71%	93%	75%	95%	-	96%	89%
LT3	25%	79%	89%	95%	-	93%	93%
LT4	64%	76%	86%	95%	100%	96%	96%
LT5	18%	55%	14%	95%	100%	89%	89%
LT6	25%	79%	89%	90%	100%	86%	93%
LT7	0%	0%	18%	95%	-	89%	64%

After students had gone through the first chapter of the TLS, intended to promote their development of a conceptual model of sound attenuation in materials in terms of energy (CM1), the second chapter started with an open-ended question to elicit their previous ideas on the acoustic behaviour of materials (T2.1.1). As shown in Table 10, in the open-ended question, we found that more than two-thirds of students identified properties of materials roughly related to density (e.g. compactness) and to rigidity (e.g. hardness, elasticity) as acoustic properties of materials, i.e. as properties influencing the acoustic behaviour of materials (LT1 & LT2). Nevertheless, as reported in previous studies (Hernández et al., 2011b; Linder, 1993), students often use similar scientific terms to refer to acoustic properties of materials, attributing the same meaning to them. Such is the case with the words 'dense' used as a synonym for compact or heavy and 'rigid' used as a synonym for plastic, non-elastic, or hard. Moreover, at this point students attributed both extensive (e.g. thickness) and intensive (e.g. density) properties to the acoustic behaviour of materials, using the word 'material' as a synonym for object.

Later in the implementation, students discussed with their classmates the new terminology and perspectives introduced by the statements included in T2.1.2 and were asked to formulate a consensus model of the acoustic behaviour of materials in terms of their properties. As a result of this activity, most students (79%) started attributing other properties to the acoustic behaviour of materials, such as porosity (LT3). Nevertheless, in some cases students blurred the terms 'dense' and 'little porous', as if the density of materials were uniquely related to their porosity.

When students predicted the acoustic behaviour of samples of specific materials in T2.1.3, most of the students (more than 75%) identified properties related to density, rigidity and porosity of materials, among other characteristics, as influencing the acoustic behaviour of materials (LT1, LT2 and LT3). Their difficulty with the accurate use of terminology (e.g. flexible as a synonym for elastic or soft) was again widely evidenced, however.

Later, students used a data-logging system connected to a sound level meter to test the acoustic behaviour of the materials empirically. Next, in T2.1.6.b students were asked to describe the properties that all the tested sound reflectors have in common and also the properties that all the tested sound absorbers have in common. At this point, most of the students (about 90%) not only were more accurate in terms of using the specific terms that refer to properties of materials influencing their acoustic behaviour (LT4, LT5 and LT6) but they also reduced the number of properties that they associated with the acoustic behaviour of materials so that 95% of them only mentioned the three so-called acoustic properties - density, rigidity, and porosity (LT7).

After discussing the scientific meaning of these properties and observing the properties of the tested materials, students wrote down their conclusions again on the properties of materials that characterize their acoustic behaviour (T2.1.8). At that point, all the students appropriately related the density, rigidity and porosity of materials to their acoustic behaviour (LT4, LT5 and LT6).

Finally, in the final assessment when students were asked to predict the acoustic behaviour of certain materials in Q4.a, about 90% of them did it appropriately uniquely in terms of density, rigidity and porosity relating them appropriately to the acoustic behaviour of materials (LT7). In Q5.a, in which students were asked to identify in an advertisement of a product the properties that characterized it as a good sound absorber, most (about 90%) mentioned density, rigidity and porosity. Some of them (about 30%) also highlighted other characteristics of the material that they considered made the material a good product (e.g. durability). We interpret that Q5.a might not be clear enough as many students did not distinguish between the properties that made the material a good product from those properties that actually influenced its acoustic behaviour.

Students' stages of development of the conceptual model of the acoustic behaviour of materials in terms of their physical properties (CM2) at each phase of the TLS

After carrying out the above analysis, we grouped the subsets of learning targets that most of students achieve at each phase of the implementation of the teaching sequence. Accordingly, we characterized four common students' mental models that corresponded to increasingly elaborate mental models of the acoustic behaviour of materials in terms of their physical properties. Table 11 presents the empirically-based description of the stages of development of this conceptual model and also includes students' answers to illustrate their evolution of CM2.

Table 11. Description of the stages of development of CM2 and students' answers.

Stage of development of CM2	Description of students' models	Students' answers
S1	Students explain and predict the acoustic behaviour of materials in terms of intensive and extensive properties, such as density and rigidity, although these terms are not used appropriately – LT1 & LT2	**T2.1.1**) Sound reflectors are elastic, dense and have light colours whereas sound absorbers are plastic, soft and have dark colours (S20)
S2	Students explain and predict the acoustic behaviour of materials in terms of intensive and extensive properties, such as density, rigidity, and porosity, although these terms are not used appropriately – LT1, LT2 & LT3	**T2.1.2.c**) Sound reflectors are dense, thick and have many particles and a smooth surface whereas sound absorbers are porous, soft, flexible and have separated particles (S20)
S3	Students adequately explain and predict the acoustic behaviour of materials in terms of intensive and extensive properties, such as density, rigidity, and porosity, using these terms appropriately – LT1, LT2, LT3, LT4, LT5 & LT6	**T2.1.3**) Aluminium would behave as a sound reflector because it is not porous, it is dense and its surface is smooth. Polyurethane would behave as a sound absorber because it is not very dense and it has holes (S20)
S4	Students adequately explain and predict the acoustic behaviour of materials uniquely in terms of intensive properties, such as density, rigidity, and porosity, using these terms appropriately – LT7	**Q4.a**) Material A would be the best sound reflector as it is dense, rigid and non-porous. Material C would be the best sound absorber because it is less dense, it is flexible and it has pores which facilitate sound propagation (S20)

After characterizing each stage of development of CM2, we analysed the distribution of students in each stage of development of CM2 throughout the implementation of the teaching sequence. This distribution is represented in Figure 3.

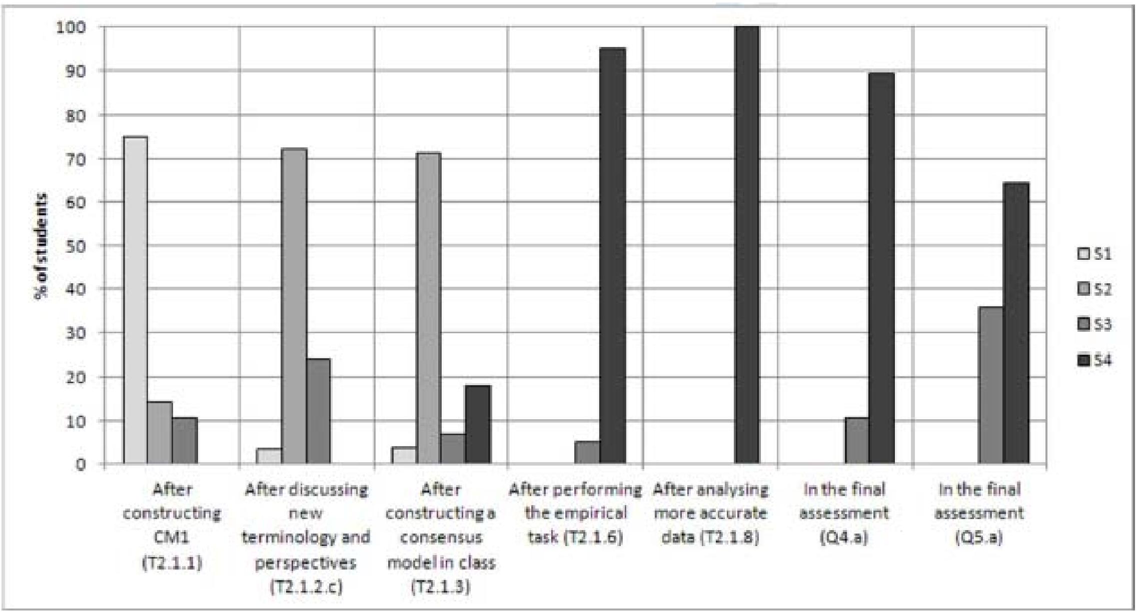

Figure 3. Students' development of CM2 throughout the implementation of the TLS.

In Figure 3, we can see that as a starting-point most students (75%) related the acoustic behaviour of materials to several intensive and extensive properties, such as density and rigidity, although these terms were not used appropriately (S1). After new terminology and perspectives were introduced and discussed (T2.1.2), more students started recognizing porosity as another acoustic property. In spite of mentioning these three key acoustic properties of materials, most of the students (more than 70%) still tended to blur certain scientific terms and also to associate many other characteristics with the acoustic behaviour of materials (S2). In T2.1.3, after discussing the influence of certain properties on the acoustic behaviour of materials and having reached a consensus model, most students seemed to hold a mental model that corresponded to the second stage of development (S2) of CM2.

The results from the analysis of students' answers to T2.1.6 show that, after students carried out the experiment to test the acoustic behaviour of the materials, almost all of them (95%) adequately explained the acoustic behaviour of materials uniquely in terms of intensive properties such as density, rigidity, and porosity, using these terms appropriately (S4). In the final assessment, most students had developed the most elaborate version (S4) of CM2.

Influence of the activities of the TLS on students' learning pathways towards the construction of the conceptual model of the acoustic behaviour of materials in terms of their physical properties (CM2)

With the purpose of validating the students' learning pathways towards the construction of CM2, we tracked each student's pathway throughout the TLS. Table 12 shows the types of evolution experienced by students while developing their model of the acoustic behaviour of materials in terms of their physical properties.

Table 12. Types of learning pathways experienced by students while developing CM2.

Type of evolution of students' models	Before and after discussing new terminology and perspectives	Before and after constructing a consensus model	Before and after the empirical task	Before and after analysing more accurate data and discussing the scientific meaning of certain properties	Before and after applying the model in later tasks
Progression	**75%**	28%	**79%**	0%	0%
Regression	7%	18%	0%	0%	14%
No evolution	18%	**54%**	21%	**100%**	**86%**

In general terms, these results highlight that students' discussion of new terminology and perspectives, introduced by means of certain statements (T2.1.2), and also students' engagement in performing and drawing conclusions from an experiment had the greatest impact on students' development of CM2 as 75% and 79% of students respectively evidenced progression from a certain stage of the conceptual model towards a more elaborate version after their engagement in each of these activities.

To sum up, Figure 4 represents the most common learning pathway towards the construction of the conceptual model of the acoustic behaviour of materials in terms of their physical properties throughout the implementation of the TLS.

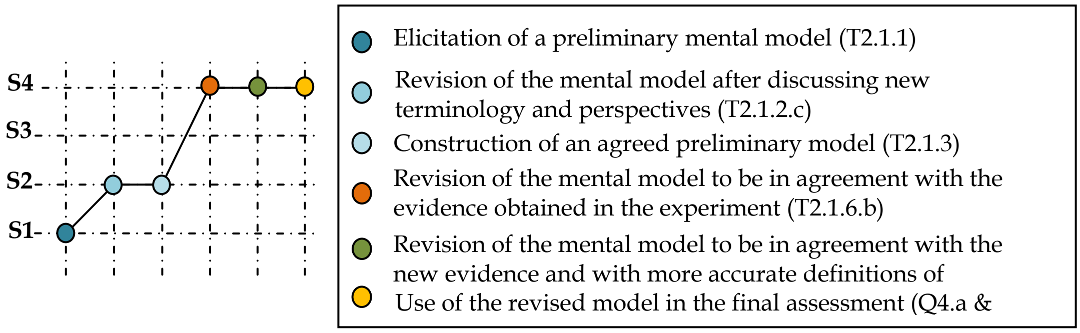

Figure 4. Description of the process of students' development of CM2 throughout the implementation of the TLS.

Students' development of the theoretical conceptual model of the acoustic behaviour of materials in terms of their internal structure (CM3)

Students' achievement of each learning target associated with the conceptual model of the acoustic behaviour of materials in terms of their internal structure (CM3)

As described previously, after students had gone through the activities intended to promote the development of CM2, they were engaged in other activities intended to promote their construction of CM3. The findings of the analysis of students' achievement of learning targets associated with the conceptual model of the acoustic behaviour of materials in terms of their internal structure (CM3) are illustrated in Table 13.

Table 13. Learning targets related to students' development of CM3.

LT – CM3	T2.1.1	T2.1.2	T2.2.2 & T2.2.4 & T2.2.5	T2.2.6 & T2.2.7	Q5.b
LT1	0%	100%	-	62%	67%
LT2	0%	54%	-	62%	63%
LT3	0%	68%	-	88%	59%
LT4	0%	18%	79%	42%	56%
LT5	0%	18%	75%	73%	41%

As shown in Table 13, the results illustrate that all students uniquely related the acoustic behaviour of materials to the internal structure of materials (LT1) when they were asked to express their agreement or disagreement with certain statements about the influence of some characteristics such as the separation between particles in the acoustic behaviour of materials (T2.1.2). Conversely, when the question was completely open (T2.1.1), students did not mention any characteristics related to the internal structure of materials as influencing the acoustic behaviour of materials.

When the students discussed with their classmates the new terminology and new perspectives introduced by the statements included in T2.1.2, more than half were able to relate density, rigidity or porosity of materials to their internal structure (LT2) and to use the particulate model of matter to explain mechanisms of sound attenuation in materials (LT3). Nevertheless, almost half described density and rigidity in terms of distance between particles. Moreover, most of these students considered sound-attenuating materials as sound barriers that prevented the passage of sound through them (Hernández et al., 2011b).

After the thought experiment in which students used an analogy[3] to investigate the influence of the internal structure of materials on their acoustic behaviour, about 80% of them appropriately described density, rigidity or porosity of materials in terms of their microstructure (LT4) and 75% used the particulate model of matter to appropriately explain mechanisms of sound attenuation in materials (LT5) in T2.2.2, T2.2.4 and T2.2.5. Thus, these students described the internal structure of materials in terms of the mass of their particles or the strength of the bonds between particles to explain sound attenuation in terms of more or less vibration of the particles that form each material.

Later in the implementation (T2.2.6 and T2.2.7), after discussion of the scientific perspective on how the properties of sound absorbers affect their acoustic behaviour, almost 75% of students used the particulate model of matter appropriately to explain mechanisms of sound attenuation in materials (LT5). A lower number of students (62%) described density, rigidity or porosity of materials in terms of their microstructure (LT2) but of these students more than two-thirds did it appropriately (LT4).

Similarly, in the final assessment (Q5.b) about 60% of students were able to explain some mechanism of sound attenuation in materials using the particulate model of matter and describing the internal structure of materials (LT2 and LT3). Of these students, almost 90% appropriately described some acoustic properties of materials in terms of their microstructure (LT4), and about 70% appropriately explained sound attenuation in materials in terms of difficulty or ease of particle vibration (LT5).

Students' stages of development of the conceptual model of the acoustic behaviour of materials in terms of their internal structure (CM3) at each phase of the TLS

After carrying out the above analysis, we grouped the subsets of learning targets that most of students achieve at each phase of the implementation of the teaching sequence. Accordingly, we characterized progressively three common students' mental models that correspond to progressively more elaborate conceptual models of the acoustic behaviour of materials in terms of their internal structure. Table 14 presents the empirically-based description of the stages of development of this conceptual model and also includes students' answers to illustrate their evolution of CM3.

Table 14. Description of the stages of development of CM3 and students' answers.

Stage of development of CM3	Description of students' models	Students' answers
S1	Students explain the acoustic behaviour of materials using the particulate model of matter and explaining mechanisms of sound attenuation in materials – LT1, LT2 & LT3	**T2.2.5**) If the material is porous it will behave as a sound absorber as its particles are more separated, and so the material has empty spaces through which sound can enter (S20)
S2	Hybrid stage between S1 and S3: students use both the preliminary (S1) and the more elaborate (S3) version of the model to explain the influence of certain characteristics of the material on their acoustic behaviour	**Q5.b**) The fact that this material has low density means that its particles are more separated, and therefore sound can enter this material; that is to say, sound can be absorbed. The material is also very flexible and therefore its particles can move more (S23)
S3	Students explain the acoustic behaviour of materials using the particulate model of matter and appropriately explaining mechanisms of sound attenuation in materials – LT1, LT4 & LT5	**Q5.b**) As the material is porous, not very dense and flexible, its particles can vibrate a lot, and so the material absorbs sound (S16)

After characterizing each stage of development of CM3, we analysed the distribution of students in each stage of development of CM3 throughout the implementation of the teaching sequence. This distribution is represented in Figure 5.

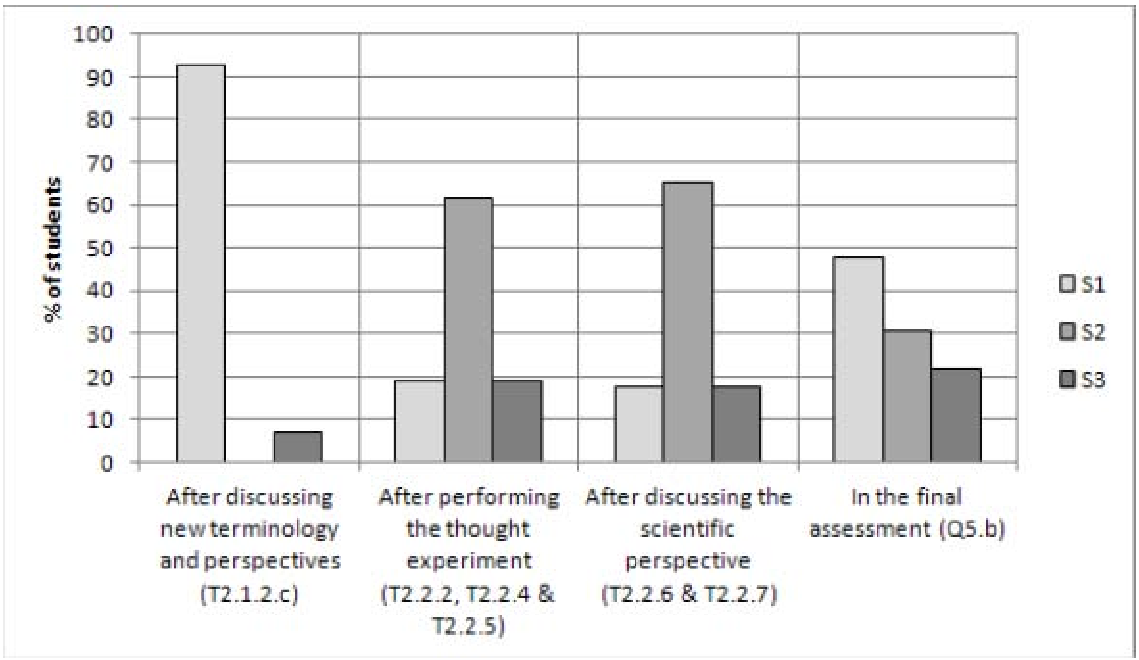

Figure 5. Students' development of CM3 throughout the implementation of the TLS.

As shown in Figure 5, when students elicited their preliminary models in T2.1.2, more than 90% of students explained the acoustic behaviour of materials using the particulate model of matter and describing mechanisms of sound attenuation in materials. Nevertheless, the model expressed by these students (S1) was not consistent with the scientific perspective as it dealt with sound as an entity instead of as a process, and consequently sound attenuation was conceived as a process hindering the passage of sound or capturing sound instead of as a process of energy dissipation that involved vibration of particles.

After students had carried out the thought experiment described above, more than 80% started explaining the acoustic behaviour of materials using the particulate model of matter and appropriately explaining mechanisms of sound attenuation in materials (S3). Even though these students used the most elaborate version of the conceptual model (S3) to explain the influence of certain properties on the acoustic behaviour of materials in terms of their internal structure, most of them also continued using the preliminary version of the model (S1) to explain the influence of other properties. That is to say, most of them used a hybrid model (S2). Similar results were evidenced after students were introduced to and discussed the scientific perspective. In the final assessment, about half of the students answered in terms of S1 whereas the other half were found to use the more sophisticated version of the model (S3) or the hybrid version (S2).

Influence of the activities of the TLS on students' learning pathways towards the construction of the conceptual model of the acoustic behaviour of materials in terms of their internal structure (CM3)

With the purpose of validating the students' learning pathways towards the construction of CM3, we tracked each student's pathway throughout the TLS. Table 15 shows the types of evolution experienced by students while developing their model of the acoustic behaviour of materials in terms of their internal structure.

Table 15. Types of learning pathways experienced by students while developing CM2.

Type of evolution of students' models	Before and after performing the thought experiment	Before and after discussing the scientific perspective	In the final assessment
Progression	**72%**	29%	21%
Regression	4%	24%	**53%**
No evolution	24%	**48%**	26%

The results expressed in Table 15 highlight that the students' realization and discussion of the thought experiment using an analogy was the activity that had a greater impact (72%) in promoting the revision of students' mental models. The students' engagement in discussing the scientific perspective did not represent a significant activity in terms of promoting progression as the models of almost half of the students remained the same after this activity. Finally, the fact that about 50% of students described a weaker version of their model in the final assessment can be interpreted from two perspectives: (1) this conceptual model (CM3) might be too demanding for the students at this level as it implies using the particulate model of matter together with two other models: the model of sound attenuation in materials in terms of energy (CM1) and the model of acoustic behaviour of materials in terms of their physical properties (CM2); and/or (2) the lack of application of this conceptual model (CM3) in different situations throughout the teaching sequence might have contributed to the lack of consolidation of this model at the end of the implementation. In the words of Duschl et al. (2011, p.152), 'if the learning goals are too sophisticated or if the teaching sequence is ill conceived, then the intended learning outcomes run the risk of being too abstract or beyond the "boundaries" of outcome learning expectations for the targeted students'.

To sum up, Figure 6 represents the most common learning pathway towards the construction of the conceptual model of the acoustic behaviour of materials in terms of their internal structure throughout the implementation of the TLS.

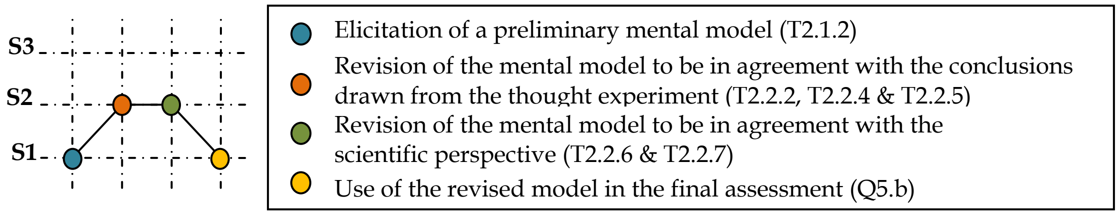

Figure 6. Description of the process of students' development of CM3 throughout the implementation of the TLS.

Discussion of Results

The reported findings support the fact that experimenting with a TLS leads to two types of results (Méheut & Psillos, 2004): results in terms of research validity and results in terms of pragmatic value. Consequently, to answer our two research questions, we will discuss the results described earlier in terms of their research validity (e.g. understanding modelling processes, refining design principles) and in terms of their pragmatic value (e.g. implications for teaching).

On students' learning pathways from their preliminary mental models towards the intended conceptual models

To answer our first research question, we discuss the learning processes that students underwent when developing their mental models for each of the three intended conceptual models dealt throughout the designed teaching sequence.

Concerning the stages of students' development of these three conceptual models, our results show that more than half reached the most elaborate version of the (theoretical) conceptual model of sound attenuation in materials in terms of energy (CM1), most reached the most elaborate version of the (empirical) conceptual model of the acoustic behaviour of materials in terms of their physical properties (CM2) and less than one-third reached the most elaborate version of the (theoretical) conceptual model of the acoustic behaviour of materials in terms of their internal structure (CM3). The remaining students reached lower stages of development for each of the three intended conceptual models. That is to say, all the students progressed through several stages of development of their mental models, and some of them reached the most elaborate version of each conceptual model.

In short, the conceptual model of the acoustic behaviour of materials in terms of their physical properties (CM2) was more easily developed by students than the conceptual model of sound attenuation in materials in terms of energy (CM1) and, in turn, students developed CM1 more easily than the conceptual model of the acoustic behaviour of materials in terms of their internal structure (CM3).

These differences can be interpreted in terms of the attributes of each conceptual model, in terms of the distance between students' preliminary mental models and the intended conceptual models, and in terms of the quality of the instruction that took place. At this point, we will comment on the two first possible interpretations to account for these differences, and we will discuss the instructional issue later. As discussed earlier, the conceptual model of the acoustic behaviour of materials in terms of their physical properties (CM2) involves real entities (i.e. materials) and their observable properties as it is an empirical model. Taking into account that students' preliminary mental models often include macroscopic descriptions of natural objects or events, which are easily visible or related to their everyday experience (Tiberghien et al., 2009), we consider that in the case of this conceptual model (CM2) students' preliminary models could act as productive intuition for understanding, which can easily become more sophisticated through teaching.

By contrast, the theoretical models CM1 and CM3 consist of descriptions of unobservable events in terms of abstract entities such as energy and particles. Several research studies (e.g. Harrison & Treagust, 2002; Millar, 2005) have reported a variety of difficulties in students' understanding of such concepts. The differences between students' development of the most elaborate version of CM1 and CM3 can be explained by the fact that, in the case of CM1, students' preliminary mental models of sound attenuation reflect an intuitive view of the phenomenon of sound attenuation which is not inconsistent with the most elaborate version of the conceptual model. On the contrary, this intuition can be considered a simpler version of the intended conceptual model based simply on measurable magnitudes (e.g. sound intensity level) that students can easily relate to an abstract entity such as energy. In the case of CM3, students' preliminary mental models already included abstract entities such as particles but these models conflicted with the more elaborate version of the conceptual as they correspond to different models of sound (i.e. sound as an entity (Maurines, 1993; Hrepic, Zollman, & Rebello, 2010) vs. sound as a process) and to different models of the structure of matter (i.e. in terms of distance between particles vs. mass of particles and strength of bonds between particles). That would explain the high percentage of students who, at the end of the implementation of the teaching sequence, used a hybrid version of the model (i.e. using at the same time their preliminary mental model and the most elaborate version of the conceptual model).

On the salient modelling and inquiry activities of the TLS on APM

Our second research question presents us with the issue of the role played by the modelling and inquiry activities of the TLS on APM in promoting students' evolution of their mental models towards the intended conceptual models.

The results showed that each of the three intended conceptual models entails different learning difficulties. This suggests that the design of the activities to promote the development of each of these conceptual models should differ from one to another.

Looking at the influence on students' learning pathways of the activities that they carried out (Figures 2, 4 and 6), we found that different types of modelling activities (Löhner et al., 2005) played a decisive role in promoting students' development of each conceptual model. In the case of the theoretical model of sound attenuation in materials (CM1), our results indicated that the activity that seemed to facilitate more the development of students' mental models was the exploratory modelling activity (i.e. 'What does science tell us?') in which students revised their models in line with the scientific perspective and used it in several tasks. We suggest that this activity had a great impact on students' development of CM1 taking into account the attributes of this conceptual model and the activities that students had previously carried out (i.e. eliciting their preliminary models, obtaining new evidence from an experiment and drawing conclusions from it). In other words, the activity in which students were introduced to the scientific perspective and discussed it with the teacher and their classmates turned out to be the most effective one, helping students progress in their explanations of how sound is attenuated when reaching an object.

In the case of the empirical model of the acoustic behaviour of materials in terms of their physical properties (CM2), the activity that seemed to facilitate more a positive development of students' mental models was the inquiry modelling activity in which students carried out an experiment and drew conclusions from the new evidence obtained. Another activity that also seemed to have a great impact on students' development of mental models was the exploratory and expressive modelling activity in which they were asked to reach a consensus model, once they had individually elicited their preliminary mental models and had explored new terminology and different perspectives in a closed question.

Finally, in the case of the theoretical model of the acoustic behaviour of materials in terms of their internal structure (CM3), the activity that seemed to facilitate more the positive development of students' mental models was the exploratory modelling activity in which students carried out a thought experiment and drew conclusions from discussing it by means of an analogy. The results of students' development of CM3 make us wonder whether a different approach to the use of the analogy would have resulted in more positive learning progression.

Conclusions and implications for design, research and instruction

Tracking students' learning pathways throughout the teaching-learning sequence has turned out to be a very useful methodological procedure for studying students' development of conceptual models and refining the design principles of the specific teaching-learning sequence on acoustic properties of materials. Thus, we consider it an appropriate method for carrying out specific research studies within the design-based research paradigm.

We have found that the different intended conceptual models involve different learning demands (Leach & Scott, 2002), which can be interpreted by taking into account the attributes of each model and the distance between students' preliminary mental models and the intended conceptual models. Moreover, in our research we have characterized students' development of mental models towards the intended conceptual models through different 'stepping stones' or stages of development of the conceptual model. This result backs the importance of intermediary steps in supporting student understanding. One important implication for teaching and design is that the empirically-based students' learning pathways, expressed as increasingly sophisticated versions of each conceptual model, can help teachers monitor or assess how students progress in what they are learning in real contexts and adapt their instruction in response to students' evolution and needs in order to support student learning. No one doubts that developing rich conceptual knowledge takes time and requires instructional support and sound assessment practices. In line with this, we recognize that students' learning outcomes at the end of the designed teaching sequence are not to be seen as an end point but as an intermediate one, and require further support and instruction so that students continue learning.

Regarding the design principles related to the types of modelling activities of the teaching sequence, we have gained an insight into the role played by the different types of modelling activities suggested by Löhner et al. (2005) in promoting students' development of conceptual models throughout the TLS on APM. According to our results, the exploratory modelling activities seem to play a more significant role in contributing to students' development of theoretical models, whereas inquiry modelling activities seem to have greater impact in promoting students' development of empirical models. By exploratory modelling activities, we do not mean transmissive activities in which the scientific perspective is uniquely introduced by the teacher or the material. Rather, we plead for designing guided or oriented activities in which teachers and students discuss and try to reconcile different perspectives and languages.

We have not found that inquiry modelling activities have a great impact on students' development of the theoretical models. That would suggest that a pure inquiry teaching approach could turn out to be less than effective in promoting students' development of theoretical conceptual models, which define abstract entities that cannot be directly constructed from the results of any empirical activity. Other authors have already urged caution about pure inquiry approaches, adducing a similar line of reasoning (Viennot, 2010).

In any case, we consider that expressive modelling activities also play a decisive role in students' learning pathways throughout the TLS on APM.

Regarding the design principles related to the structure of each sequence of tasks in the teaching sequence, our results support the fact that students' elicitation of their own prior knowledge, followed by their carrying out of empirical tasks and later discussion of the scientific perspective, have a positive impact in terms of contributing to students' development of their mental models. Therefore, we highlight the importance of including such kinds of expressive and inquiry activities prior to any exploratory activity when a teaching sequence is designed That is to say, students should be put in the situation of eliciting their own mental models and feeling the need to revise them in agreement with the new (empirical or non-empirical) evidence obtained (from real or thought experiments) before the scientific perspective or intended conceptual model is introduced.

In short, these results highlight that the relationship between modelling and inquiry is complex as different modelling and inquiry activities seem to facilitate students' development of a certain type of conceptual model but they need to be appropriately combined and sequenced to become effective. Further research is necessary to better understand the interplay between modelling and inquiry processes in teaching, learning and doing science, and about science.

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Footnotes

1. We adopt this term in a broad sense to refer to various kinds of research approaches that are related to design, development and evaluation of educational interventions, programmes, processes and products (e.g. design research, development/developmental research, etc).
2. We use this term here as a synonym for conceptual trajectories, conceptual progressions, and learning progressions.
3. The text starts by introducing the formal definition of sound attenuation in a material in terms of the decrease in the intensity level of sound when it is

transmitted through a material. The text also explains how sound is attenuated in terms of the interactions between particles of the different media through which sound propagates to transfer energy, making explicit the phenomena involved in sound attenuation, reflection and absorption. Therefore, sound intensity and energy of sound are presented as related concepts. Moreover, sound-attenuating materials are classified as sound reflectors and sound absorbers according to their acoustic behaviour. The visual representation is a diagram representing the process of sound attenuation in a wall as an energy balance. This image is composed of lines representing the amount of energy of incident, reflected, and transmitted sound and dots within the wall representing absorbed energy. The thickness of each line represents the amount of energy associated with incident, reflected and transmitted sound respectively and it is intended to convey the idea that the total incident energy is conserved.

4. This analogy compares particles that form each medium or material with pool balls connected by means of springs. According to this analogy, density is related to the mass of the balls and rigidity is related to the elastic constant of the springs connecting the balls. According to the ball-and-spring model, porosity is related to the presence of air particles inside the pores of a material, which in turn is formed by bonded particles with a different mass.

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Appendix

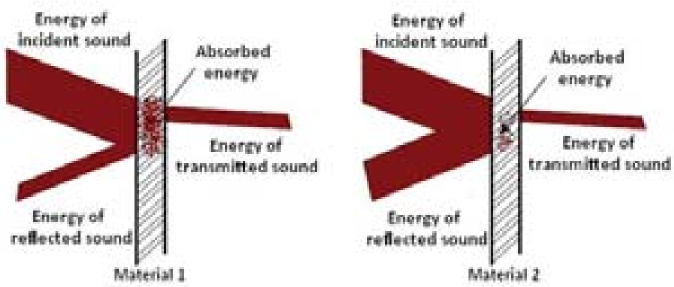
Tasks to collect evidence of the development of conceptual models

T1.1.2. (a) What happens to the sound emitted by the loudspeaker when it reaches the walls of the disco?

(c) If I am outside the disco, I cannot hear the music as loudly as when I am inside. Why is it not possible to hear it with the same intensity as inside?

T1.3.5. The technician places a loudspeaker inside the disco and adjusts it to emit sound with a frequency of 500 Hz and sound intensity level of 100 dB. The measurements taken in the neighbour's house at night reveal that the sound intensity level there is 58 dB, the house being separated from the disco only by common building elements (concrete walls, bricks). What has happened to that part of the sound that has not been transmitted?

T1.3.6. The following diagrams represent the process of energy distribution when sound propagated through air reaches an object.



(a) Which diagram represents a sound reflector and which represents a sound absorber?
(b) Explain your answer.

T1.3.7. How can we test empirically if a material attenuates sound a lot or a little?

T1.3.9. As a summary of the first part of this sequence, try to organize your ideas by explaining what you have learnt up to now. Elaborate a text to answer the following question:
'How can we manage to avoid hearing too much sound outside the disco?'.

T2.1.1. As you saw in the previous section, sound reflectors and absorbers behave differently in front of sound: some of them reflect sound on their surface whereas others attenuate the sound that is propagating inside them and absorb part of the energy of sound.
(a) Which properties do you consider sound reflectors to have in common?
(b) And sound absorbers?

T2.1.2. Students from another secondary school have also thought of some characteristics that sound reflectors and absorbers have. What do you think about what they think?
(a) Write in the following table, if you agree (A) or disagree (D) with each of the students' sentences, justifying your answer.

STUDENTS' ANSWERS	A/D	JUSTIFICATION
1. '**Porous** materials **or** those **made of fibres** are good **sound absorbers**'		
2. 'Very **dense** materials are good sound **reflectors**'		
3. '**Sound absorbers** have **very separate particles**'		
4. 'The **thicker** a material is, the better **sound reflector** it is'		
5. '**Sound absorbers** are usually **flexible**'		
6. '**Sound reflectors** have smooth **surfaces**'		
7. '**Soft** materials are good **sound absorbers'**		
8. '**Sound reflectors** are made of **a lot of particles**'		

(b) Discuss with your partners which characteristics a material must have to be considered a sound reflector or absorber respectively, explaining your reasons.

(c) Fill in the squares below with the characteristics that you have agreed during the idea-sharing exercise.

CHARACTERISTICS OF SOUND REFLECTORS	CHARACTERISTICS OF SOUND ABSORBERS

T2.1.3. Which materials will behave as good sound absorbers or reflectors? Now that you have already discussed which characteristics of sound absorbers and sound reflectors are relevant to their acoustic behaviour, samples of materials are given below for you to observe and predict if these materials will behave as good sound absorbers or good sound reflectors. Justify your answer.

MATERIAL	A/R	JUSTIFICATION
Aluminium foil		
Felt		
Polyurethane		
Chipboard with formica		
Glass wool		

T2.1.6. (b) Of the sound reflectors you have tested, what properties do they all have in common? What properties do all the sound absorbers have in common?

T2.1.8. Final conclusions

Use the data from the previous table to draw conclusions on the properties of sound reflectors and sound absorbers. Fill in the following table with your conclusions about which physical properties sound reflectors and sound absorbers have:

PROPERTIES	SOUND REFLECTORS	SOUND ABSORBERS
Density		
Rigidity		
Porosity		

T2.2.2. (a) What does the fact that a material is denser mean in terms of internal structure?

(b) Think of an explanation for why the density of a material affects its acoustic behaviour, that is, the fact that the material reflects sound a lot or a little, using the particulate model of matter.

T2.2.4. (a) What does the fact that a material is more rigid mean in terms of internal structure?
(b) Think of an explanation for why the rigidity of a material affects its acoustic behaviour, that is, the fact that the material reflects sound a lot or a little, using the particulate model of matter.

T2.2.5. How would you account for the fact that the porosity of a material contributes to its behaviour as a good sound absorber?

T2.2.6. You have just read a scientific explanation that accounts for how density, rigidity and porosity of materials make them behave as good sound absorbers. Based on the previous explanation, explain how sound is attenuated in sound reflectors and how their physical properties make them behave like that (reflectors).

T2.2.7. Comment on the following sentences using the model of sound reflector and absorber in terms of their internal structure and physical properties.
a) Porous materials such as glass wool are good sound absorbers
b) Dense and rigid materials such as chipboard with Formica behave as good sound reflectors

Q2. (a) Represent the energy of the reflected sound wave, the absorbed energy and the energy of the transmitted sound wave in a material X which (i) attenuates very little sound (bad sound absorber and bad sound reflector), (ii) is a very good sound absorber.
(b) How would be the attenuation of sound caused by this material X?

(c) If you were outside the disco and the walls were made of material X, what would you hear? What level of sound intensity could be measured?

Q4. A group of students inquired about sound absorbers and sound reflectors.

(a) These students selected three different materials and determined their physical properties (density, rigidity and porosity). The following table includes the data and description of the properties of these materials:

MATERIAL	DENSITY (g/cc)	RIGIDITY	POROSITY
A	0.02	Rigid	No
B	0.07	Flexible	Yes
C	3.00	Rigid	No

According to their properties, which of these three materials do you think would make the best sound reflector? Which of these materials would be the best sound absorber? Justify your answer.

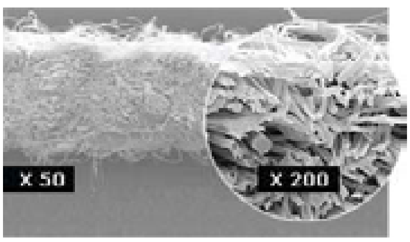
(b) The students also measured the sound intensity level by placing a sound-level meter inside and outside boxes covered with these materials, and placing the sound source inside the box. The values obtained when the sound intensity level was measured are:

MATERIAL	SOUND INTENSITY LEVEL (dB) OUTSIDE THE BOX	SOUND INTENSITY LEVEL (dB) INSIDE THE BOX
D	43-44	68-69
E	69-70	92-93
F	74-75	82-83

Given that the reference value of sound intensity inside the box is 90dB, which of these values correspond to the best sound absorber? Which of the values correspond to the best sound reflector? Justify your answer.

(c) Which material attenuates more sound? Which material attenuates less sound? Justify your answer.

Q5. A building company has developed a new generation of sound absorbers. Its advertisement says:



Absorson is a textile that offers very good sound-absorbing properties. Its structure, made of fibres or microfilaments, is very compact. It is very durable. This material is permeable to air and has a density of 0.2 g/cc. Up to now, the materials used were very thick and heavy, but the structure of microfilaments of Absorson guarantees efficient sound absorption with minimal thickness (approximately 0.5 mm) and a density 10 to 30 times lower. In addition, it is very flexible and it can be used in many different fields such as construction or the car industry. For instance, the installation of this material in a large restaurant reduced the sound intensity level by up to 10 dB.

(a) Identify in the text only the physical properties that influence the acoustic behaviour of the material and make it a good sound absorber.

(b) How would you explain the fact that these properties make this material a good sound absorber? Give reasons for your answer in terms of the internal structure of this material and in terms of the particles that form the material.

Resum

La present tesi doctoral explora diversos aspectes del procés de desenvolupament iteratiu d'una seqüència per a l'ensenyament i aprenentatge sobre propietats acústiques dels materials. Les diferents publicacions que formen part del compendi de la tesi posen en relleu les diferents etapes d'aquest procés: disseny, implementació, avaluació, refinament i contribució als principis de disseny. Identificar quines accions es duen a terme en cadascuna d'aquestes etapes i amb quins criteris i metodologies és el focus d'aquesta tesi.

Aquesta recerca parteix de la convicció de que és possible promoure l'aprenentatge d'aquest contingut amb alumnes de secundària, integrant coneixement generat per la recerca i l'experiència dels professors, establint lligams entre els àmbits de la innovació i la recerca. Aquesta tasca, però, està lluny de ser òbvia, ja que interpretar i implementar eficientment els resultats de la recerca a la pràctica educativa no és immediat. És per això que aquesta tesi es centra en analitzar el desenvolupament iteratiu d'una seqüència d'ensenyament i aprenentatge per millorar la qualitat de la mateixa, entenent per qualitat una sèrie de criteris avaluables com la validesa, la utilitat i l'eficàcia.

Per portar a terme aquest estudi, es van analitzar les observacions d'aula i les produccions escrites de diferents poblacions d'alumnes de 4t d'ESO al llarg de la implementació de cada versió de la seqüència d'ensenyament i aprenentatge durant tres cursos consecutius. També es van tenir en compte les notes de les reunions del grup de dissenyadors del material, del qual formaven part investigadors en didàctica de les ciències i professors de secundària que van implementar el material a les seves classes. L'anàlisi d'aquest conjunt de dades ens ha permès caracteritzar el procés de refinament de la seqüència i descriure la dinàmica de desenvolupament de models conceptuals per part dels alumnes, tot avaluant la influència de determinades activitats de la seqüència dissenyada.

Les publicacions que formen part d'aquest compendi són:

- Hernández, M. I., Couso, D., & Pintó, R. (2011). The Analysis of Students' Conceptions as a Support for Designing a Teaching/Learning Sequence on the Acoustic Properties of Materials. *Journal of Science Education & Technology*. doi 10.1007/s10956-011-9358-4.
- Hernández, M. I., Couso, D., & Pintó, R. (2011). Teaching acoustic properties of materials in secondary school: Testing sound insulators. *Physics Education*, *46(5)*, 559-569.
- Hernández, M. I., & Pintó, R. (en premsa). The process of iterative development of a teaching/learning sequence on acoustic properties of materials. A D. Psillos & P. Kariotoglou (Eds.), *Iterative design of teaching-learning sequences: introducing the science of materials in European schools*. The Netherlands: Springer Editorial.

Una part fonamental d'aquesta tesi està escrita en català. Les publicacions que formen part d'aquest treball s'han inclòs en la seva llengua original, l'anglès.

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