APPENDICES

APPENDIX B
TABLE OF THE MOVEMENTS OF THE PARTICLES OF/IN THE MEDIUM (as found in an open-ended pilot test)

Table B.1. Movements of the particles of/in the medium as found in an open ended pilot test

While sound propagates, particle of the air / dust move in following ways:	Movement code
• **No**, they don't move	N
• Do not move except at the first moment when sound hits it (Initial Movement Only)	N(IMO)
• **Yes**, they move • Move in a straight line • Move in constant motion but without specified direction; • Move in a wave like motion • Sound will have little OR no effect on the particles; • Vibrate OR travel toward the listener • Move with interruptions but without direction defined • Moves and comes back at the same position	Y
• Move in the Direction of sound propagation	Y(D)
• Vibrate Longitudinally (back and forth)	Y(L)
• Vibrate Longitudinally + move in the Direction of sound propagation	Y(L+D)
• Vibrate Transversally (up and down)	Y(T)
• Vibrate Transversally + move in the Direction of sound propagation	Y(T+D)
• Move Sinusoidally in the direction of sound propagation	Y(S)
• Vibrate; oscillate • Vibrate Longitudinally OR Transversally	Y(V)
• Vibrate Longitudinally AND Transversally at same time (circling, spiraling)	Y(L+T)
• Vibrate Faster than without sound	Y(VF)
• Move Faster than without sound	Y(F)
• Are Dispersed, scattered • Are set into random motion • Are pushed and travel upward/downward	Y(DSP)
• Are Pushed Backward (toward the source of sound)	Y(PB)
• Some of motions above with: • Interruptions in motion • Changing amplitude	Y (The motion +I)
• Inconclusive	INC

APPENDIX C
FREQUENCY OF THE MOVEMENTS OF THE PARTICLES IN/OF THE MEDIUM
(as found in an open-ended pilot test)

Table C.1. Frequency of the movements of the particles of the medium as found in the open ended pilot test

Movement	1. Sound of human voice influences the movement of AIR particles	2. CONSTANT sound of loudspeaker influences the movement of DUST particle	2a. BEATING sound of loudspeaker influences the movement of DUST particle	3. Sound of human voice influences the movement of WALL particles	Total number of times the movement was expressed in all contexts
N	11	27	14	32	84
N(IMO)	0	6	0	0	6
Y	37	22	39	62	160
Y(D)	14	43	14	0	71
Y(L)	36	23	10	12	82
Y(L+D)	2	1	1	0	4
Y(T)	5	10	8	1	24
Y(T+D)	0	2	0	0	2
Y(S)	1	6	1	0	8
Y(V)	22	13	5	19	59
Y(V+D)	0	2	1	0	3
Y(L+T)	3	0	3	0	6
Y(VF)	1	0	0	0	1
Y(F)	5	0	0	2	7
Y(DSP)	5	0	3	0	8
Y(PB)	1	1	0	0	2
Y(L+I)	0	0	13	0	12
Y(D+I)	0	0	23	0	23
Y(S+I)	0	0	5	0	5
Y(T+I)	0	0	3	0	3
Y(V+I)	0	0	7	0	7
Y(L+D+I)	0	0	1	0	1
Y(T+D+I)	0	0	1	0	1
Y(V+D+I)	0	0	1	0	1
INC	1	0	1	4	6
No answer	14	2	4	26	46
ALL	158	158	158	158	632
SUM NO	**11**	**33**	**14**	**32**	**90**
SUM YES	**132**	**123**	**139**	**96**	**490**

APPENDIX H-1
VALIDITY INTERVIEW PROTOCOL
AIR-VACUUM CONTEXT

Situation A1

We have two people in the situation as in the picture below. As the speaker talks, the listener hears him. **Please try to describe as fully as possible how the sound propagates in this situation. Please feel free to draw on the picture as you are explaining.**

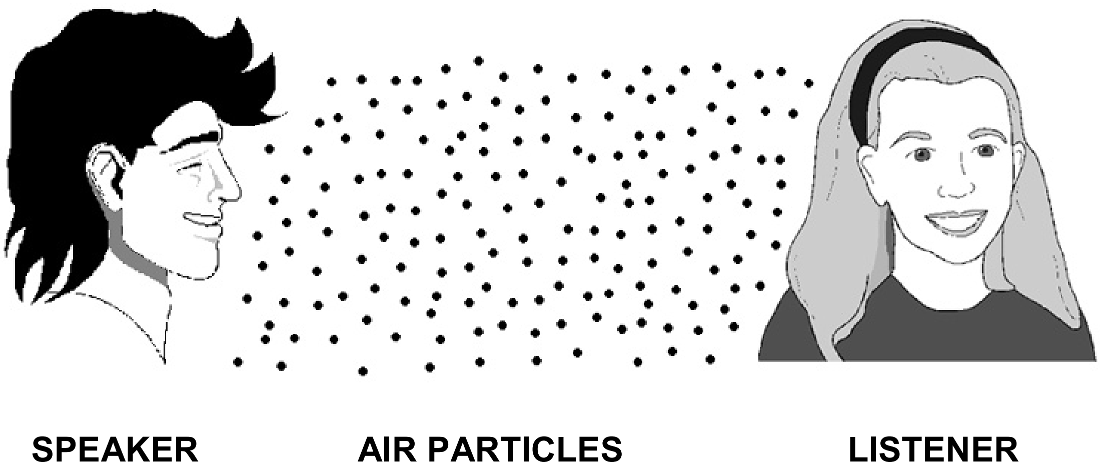
SPEAKER **LISTENER**

Follow up questions – depending on the initial answer:

1. **Does air play any role in the process of the sound propagation? If Yes: What is its role?**
2. **As the sound propagates, does it affect the motion of the air particles in any way? If Yes: In which way?**
3. **If air move toward the listener: If sound lasts long enough, will the air particles eventually reach the listener in this situation? If Yes of No: Please explain why?**
4. **How is this motion related to sound?**
5. **How do the air particles move when compared to the sound?**
6. **When does this motion occur with respect to sound propagation?**
7. **Would anything be different for sound in space without the air and in the space with the air?**
8. **Is sound something that exists only in the air, only in the ear/head of the listener, or both?**
9. **Why is the sound quieter closer to the listener than to the speaker?**

Situation A2

Now let us suppose we have examined the microscopic structure of the air and found out that the particles of which this wall consists are arranged in the way shown on the picture below. Suppose these dots represent the air particles.



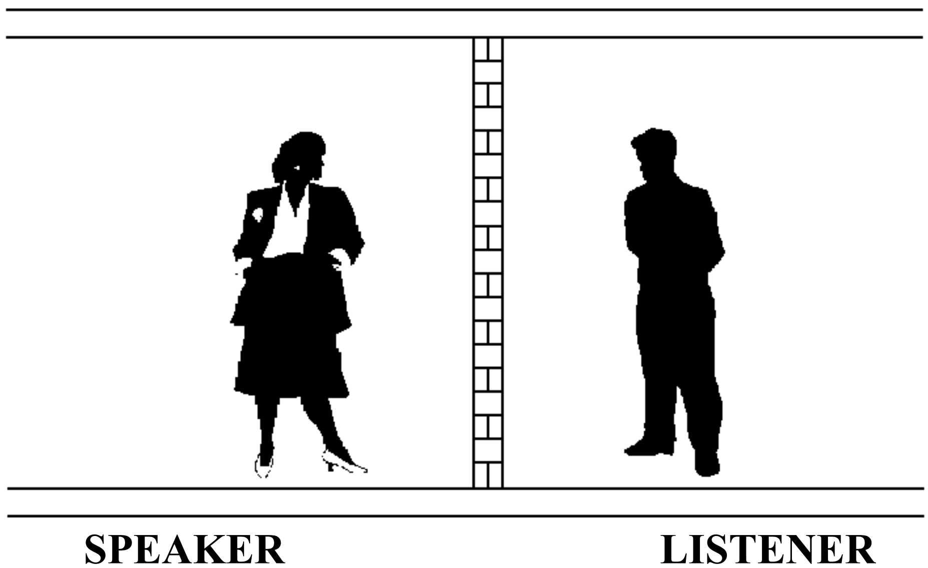
Please use this representation to describe sound propagation.

Depending of the answer, follow up questions in this situation were the subset of the follow up questions outlined for the situation A1.

APPENDIX H-2
VALIDITY INTERVIEW PROTOCOL
WALL-VACUUM CONTEXT

Situation W1

We have two people in two different rooms separated with wall. The wall is made of solid full bricks and the ceiling and the floor are made of concrete. We all know from experience that if speaker is loud enough and wall is relatively thin, listener can hear the speaker in the other room.



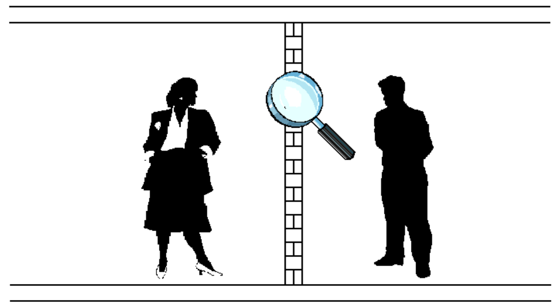
How sound reaches the listener in this situation?

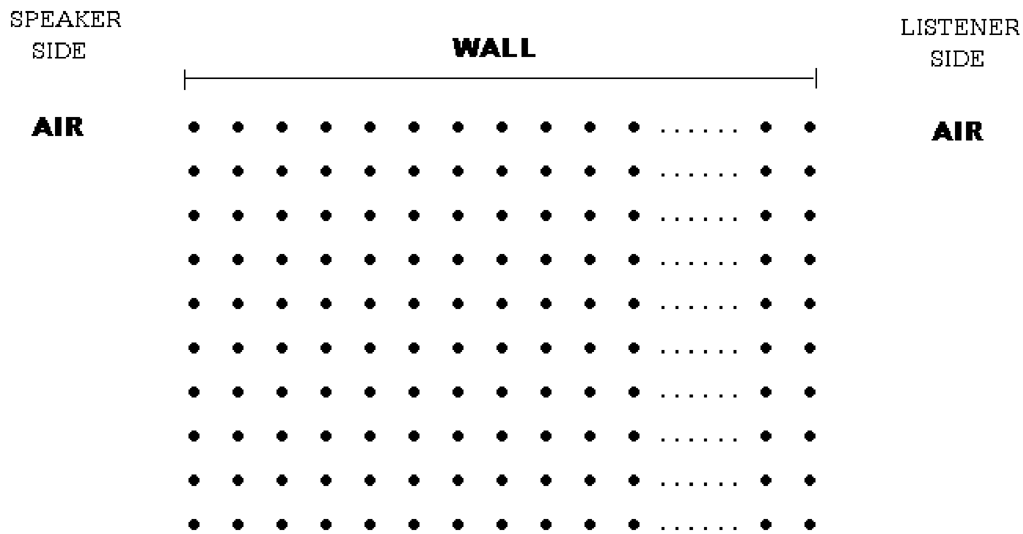
Follow up questions:

1. **Does wall play any role in the process of the sound propagation? If Yes: What is its role?**
2. **Does air play any role in the process of the sound propagation? If Yes: What is its role?**
3. **As the sound propagates, does it affect the motion of the wall particles in any way? If Yes: In which way?**
4. **How is this motion related to sound?**
5. **How do the air particles move when compared to the sound?**
6. **When does this motion occur with respect to sound propagation?**
7. **Would anything be different for sound in space without the air and in the space with the air?**
8. **Is sound something that exists only in the air, only in the ear/head of the listener, or both?**
9. **Why is the sound quieter closer to the listener than to the speaker?**

<u>Situation W2</u>

Now let us suppose we have examined the microscopic structure of the wall and found out that the particles of which this wall consists are arranged in the way shown on the picture below.





What happens on this microscopic level as the sound reaches the wall?

Depending of the answer, follow up questions in this situation were the subset of the follow up questions outlined for the situation A1.

APPENDIX I-1
PICTORIAL REPRESENTATION OF SOUND PROPAGATION THROUGH THE AIR

This appendix presents various pictorial representations of mental models of sound propagation as pertaining to the air context. These models are:

(A) Wave Model, which is the scientifically accepted model
(B) Propagating Air Model (hybrid model)
(C) Dependent Entity Model (hybrid model)
(D) Independent Entity Model, which is a dominant alternative model

The first of these representations (presented below) was used in the interview protocol. Human characters in it represent air particles and footballs represent sound entities. Different pictorial representations which do not use human characters are given in the next figures in this appendix. Each of them has a different degree of detail and therefore a different degree of complexity. Depending on the instructor's teaching goals, time available and student quality, representations with a different degree of complexity can be used.

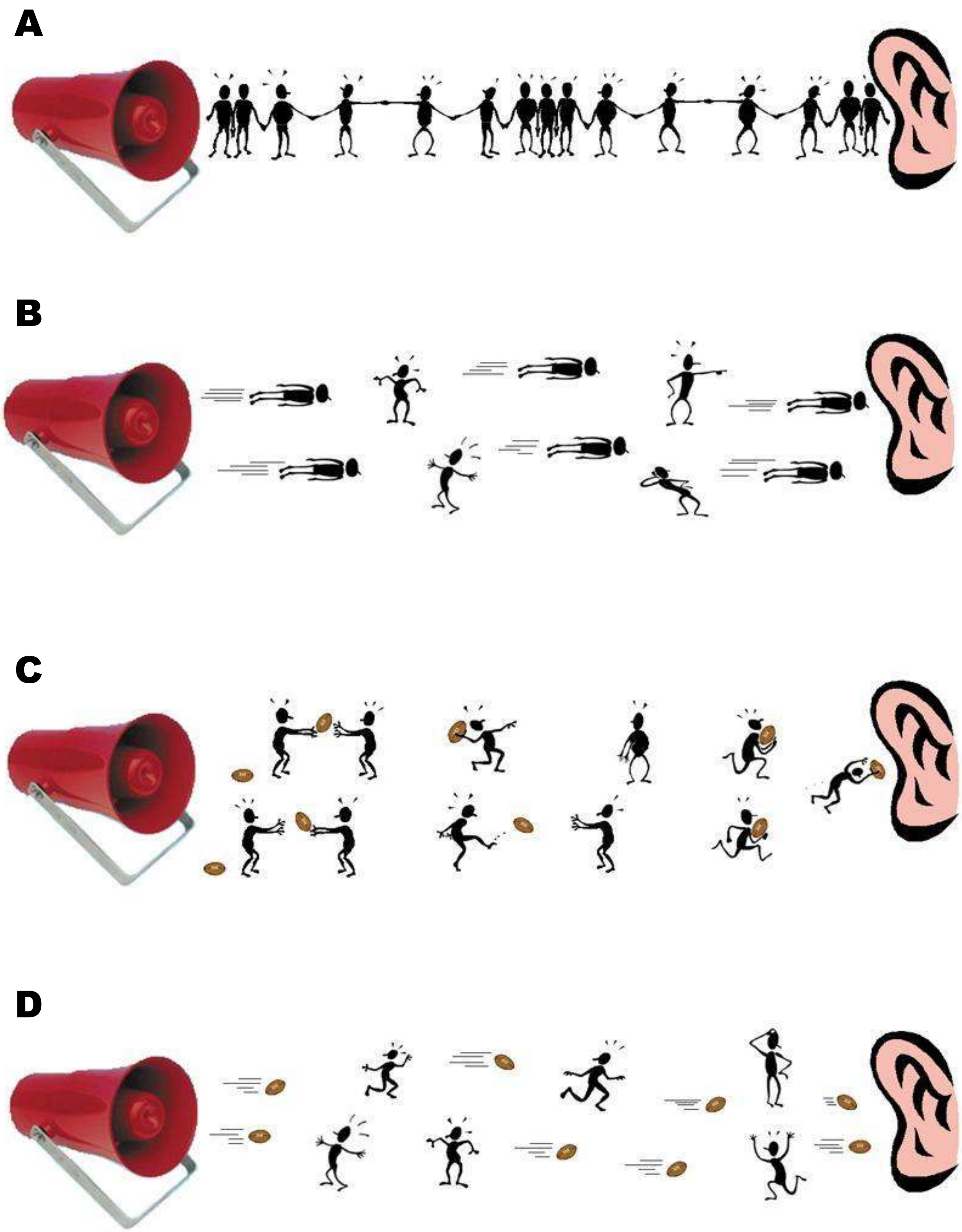


Figure I-1.1 Pictorial representation of mental models of sound propagation through the air (1)

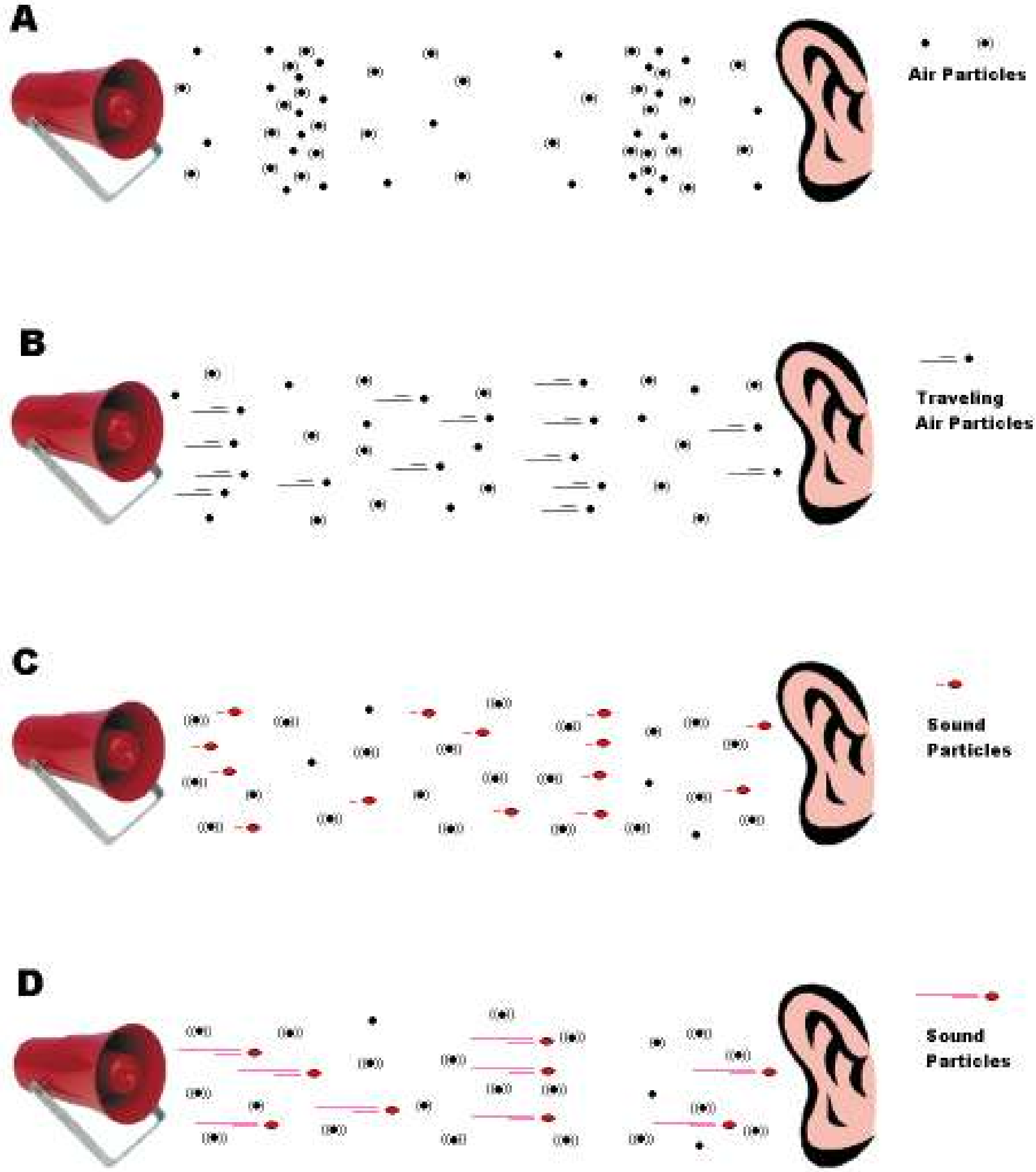


Figure I-1.2 Pictorial representation of mental models of sound propagation through the air (2)

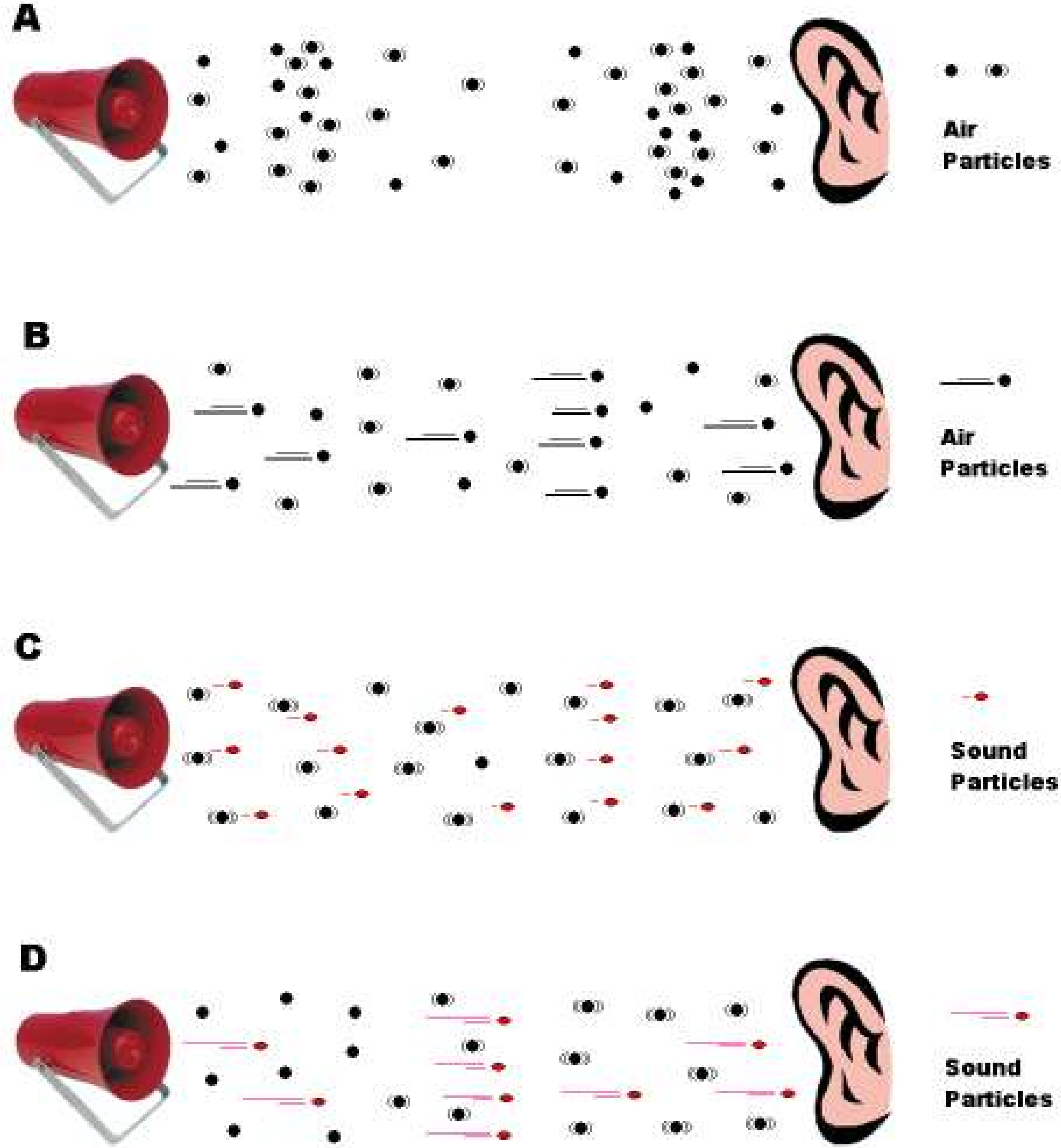


Figure I-1.3 Pictorial representation of mental models of sound propagation through the air (3)

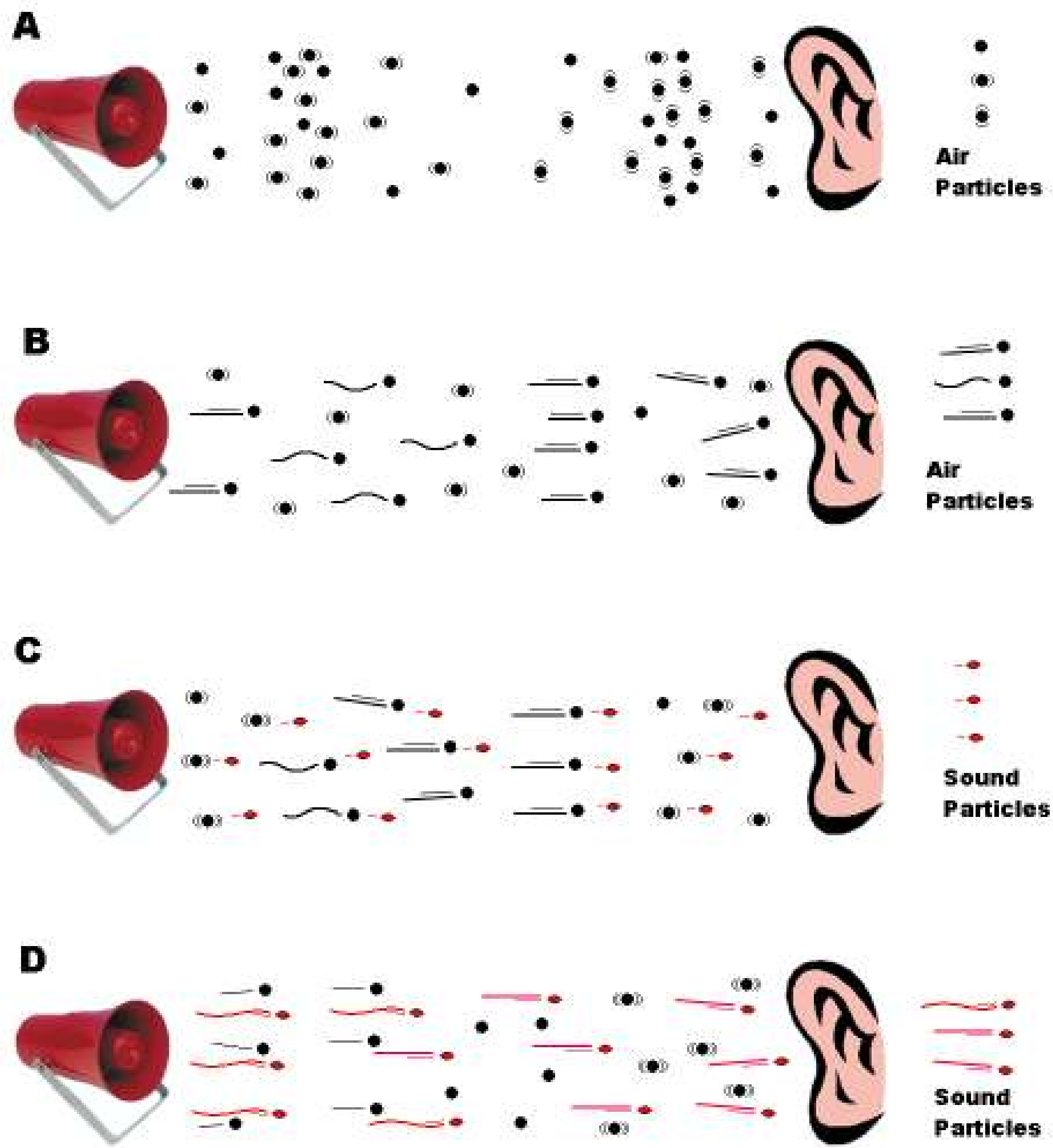


Figure I-1.4 Pictorial representation of mental models of sound propagation through the air (4)

APPENDIX I-2
PICTORIAL REPRESENTATION OF SOUND PROPAGATION THROUGH THE WALL

This appendix presents pictorial representations of mental models of sound propagation as pertaining to the wall context. These models are:

(A) Wave Model, which is a scientifically accepted model
(B) Propagating Air Model (hybrid model)
(C) Dependent Entity Model (hybrid model)
(D) Independent Entity Model, which is a dominant alternative model

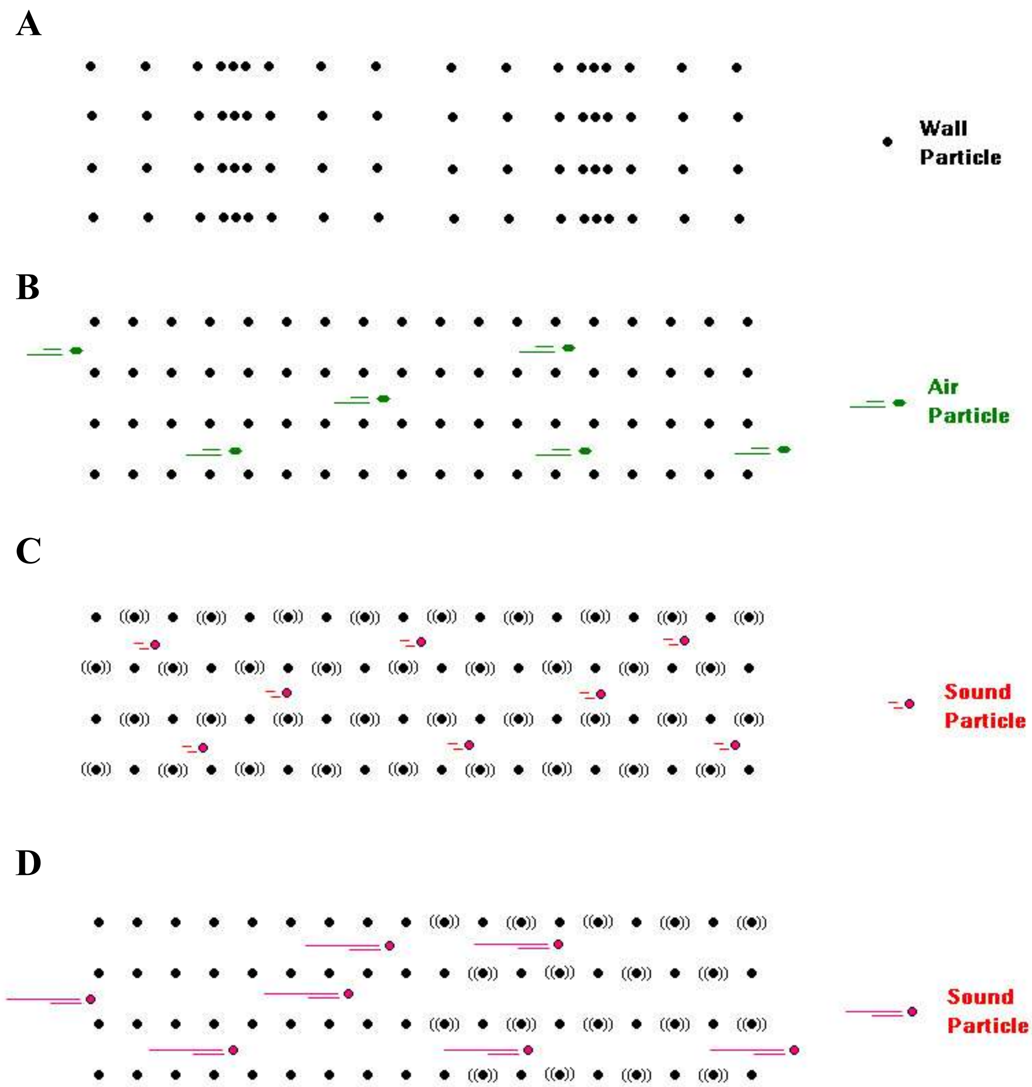


Figure I-2.1 Pictorial representation of mental models of sound propagation through the wall

APPENDIX J-1
AIR-VACUUM CONTEXT – LIST OF MODELS AND SUB-MODELS

Table J-1.1. List of models and sub-models in the air-vacuum context

MODEL	Sub model - 1st order effect	Sub model - 2nd order effect	CODE
Wave	Longitudinal		W-L
	Transversal		W-T
	Circular		W-C
	Phonon (L)		W-PH
Intrinsic	Propagating Air	Non-vibrating	PAI-NV
		Randomly Vibrating	PAI-RV
		Longitudinally Vibrating	PAI-LV
		Transversally Vibrating	PAI-TV
		Circularly Vibrating	PAI-CV
	Randomly Traveling Air		RTAI-G
Ear-born	Vibrating Air		EB-VA
	Randomly Vibrating air		EB-RVA
	Propagating Air		EB-PA
	Randomly Traveling Air		EB-RTA
Dependent Entity	Preconditioned motion	Vibrating Air	DE-P (V)
		Randomly Vibrating Air	DE-P (RV)
		Propagating Air	DE-P (P)
		Randomly Traveling Air	DE-P (RT)
	Constant Motion	Vibrating Air	DE-C (V)
		Randomly Vibrating Air	DE-C (RV)
	Generic Dependent Entity		DE-G
Independent Entity	Shaking		IE-S
	Randomly Shaking		IE-RS
	Pushing		IE-P
	Randomly Pushing		IE-RP
	Non-intrusive		IE-NI
	Generic Independent Entity		IE-G
Entity Generic			E-G
OTHER			O

APPENDIX J-2
WALL-VACUUM CONTEXT – LIST OF MODELS AND SUB-MODELS

Table J-2.1. List of models and sub-models in the wall-vacuum context

MODEL	Sub model - 1st order effect	Sub model - 2nd order effect	CODE
Wave	Longitudinal		W-L
	Transversal		W-T
	Circular		W-C
	Phonon (L)		W-PH
Intrinsic	Moving Wall (Air-Wall-Air)	Propagating Wall	I-PW
		Randomly Traveling Wall	I-RTW
		Generic Intrinsic Wall	I-GW
	Propagating Air	With Not Affected Wall	I-PA (SW)
		With Vibrating Wall	I-PA (VW)
		With Traveling Wall	I-PA (TW)
		Generic Intrinsic-PA	I-PA (G)
	Generic Propagating air		PA
Ear-born	Propagating Air	With Not Affected Wall	EB-PA (SW)
		With Vibrating Wall	EB-PA (VW)
		With Traveling Wall	EB-PA (TW)
		Generic Ear-born-PA	EB-PA (G)
	Due to the moving Wall (Air-Wall-Air)		EB-MW
Dependent Entity	Preconditioned Motion	Vibrating Wall	DE-P (V)
		Randomly Vibrating Wall	DE-P (RV)
		Propagating Wall	DE-P (P)
		Randomly Traveling Wall	DE-P (RT)
	Constant Motion	Vibrating Wall	DE-C (V)
		Randomly Vibrating Wall	DE-C (RV)
	Generic Dependent Entity		DE-G
	Propagating Air	With Not Affected Wall	DE-PA (SW)
		With Vibrating Wall	DE-PA (VW)
		With Traveling Wall	DE-PA (TW)
		Generic Depend. Entity-PA	DE-PA
Independent Entity	Shaking		IE-S
	Randomly Shaking		IE-RS
	Pushing		IE-P
	Randomly Pushing		IE-RP
	Non-intrusive		IE-NI
	Generic Independent Entity		IE-G
	With Propagating Air		IE-PA
Entity Generic			E-G
OTHER			O

APPENDIX K-1
AIR-VACUUM CONTEXT – SUB-MODEL COMBINATIONS AND DESCRIPTIONS

Table K-1.1. Combinations and descriptions of models and sub-models in the air-vacuum context

MODELS in Air-Vacuum context			CODE	ANSWER COMBINATION						SUB MODEL DESCRIPTION
	Sub model 1st order effect	**Sub model 2nd order effect**		**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	
Wave	Longitudinal		W-L	b	c	b	e	d	b	Vibration of the particles of the medium caused by the (sound) source is intrinsically sound. Sub-models are defined by the kind of vibration involved in sound propagation.
	Transversal		W-T	b	d	b	e	d	b	
	Circular		W-C	b	e	b	e	d	b	
	Phonon (L)		W-PH	e	c	b	e	d	b	See section 4.5.2.
Intrinsic	Propagating Air	Non-vibrating	PAI-NV	b	a	c,d	e	d	b	Traveling of the particles of the medium caused by the source along the certain direction is intrinsically sound. 1^{st} order effect of the sub-models differentiate between traveling away from the source (propagating air) and the random traveling. Traveling away from the source is than also classified according to the accompanied vibration.
		Randomly Vibrating	PAI-RV	b	b	c,d	e	d	b	
		Longitudinally Vibrating	PAI-LV	b	c	c,d	e	d	b	
		Transversally Vibrating	PAI-TV	b	d	c,d	e	d	b	
		Circularly Vibrating	PAI-CV	b	e	c,d	e	d	b	
	Randomly Traveling Air		RTAI-G	b	a,b,c,d,e	e	e	d	b	
Ear-born	Vibrating Air		EB-VA	d	c,d,e	b	d	b*	c	Sound is created when particles of the medium hit the listener's ear. Kind of the motion of the air particles which causes this sensation defines the (1^{st} order) sub-model.
	Randomly Vibrating air		EB-RVA	d	b	b	d	b*	c	
	Propagating Air		EB-PA	d	a,b,c,d,e	c,d	d	b*	c	
	Randomly Traveling Air		EB-RTA	d	a,b,c,d,e	e	d	b*	c	

MODELS in Air-Vacuum context (Continued)			CODE	ANSWER COMBINATION						SUB MODEL DESCRIPTION
	Sub model 1st order effect	**Sub model 2nd order effect**		**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	
Dependent Entity	Preconditioned motion	Vibrating Air	DE-P (V)	c,e	c,d,e	b	c	a*	a	Sound entity needs the motion of the medium particles in order to travel. This motion can be preconditioned i.e. the source of the sound creates the motion thus creating conditions for sound to travel. The motion can also be constant i.e. the same with or without the source. This two types of motion define 1st order sub-model. Second one is defined by associated dynamics of the air particles.
		Randomly Vibrating Air	DE-P (RV)	c,e	b	b	c	a*	a	
		Propagating Air	DE-P (P)	c,e	a,b,c,d,e	c,d	c	a*	a	
		Randomly Traveling Air	DE-P (RT)	c,e	a,b,c,d,e	e	c	a*	a	
	Constant Motion	Vibrating Air	DE-C (V)	c,e	c,d,e	b	a ~~(c)~~	e	a	
		Randomly Vibrating Air	DE-C (RV)	c,e	b	b	a ~~(c)~~	e	a	
	Generic Dependent Entity		DE-G							Student is not self consistent, and the triplet can not distinguish 1st order sub-model.
Independent Entity	Shaking		IE-S	a,e	c,d,e	b	b	c	d,e	Sound entity propagates with or without the medium. When it propagates through the medium it moves the particles of the medium so they vibrate in a certain way (shaking, randomly shaking) or travel in a certain direction (pushing, randomly pushing). Independent sound entity may not affect the dynamics of the particles of the medium (non-intrusive).
	Randomly Shaking		IE-RS	a,e	b	b	b	c	d,e	
	Pushing		IE-P	a,e	a,b,c,d,e	c,d	b	c	d,e	
	Randomly Pushing		IE-RP	a,e	a,b,c,d,e	e	b	c	d,e	
	Non-intrusive		IE-NI	e (a)	a	a	a	e	d,e	
	Non-intrusive (2)		IE-NI	e (a)	b,c,d,e	b	a	e	d,e	
	Generic Indep. Entity		IE-G							Student is not self consistent, and the triplet can not distinguish 1st order sub-model.
Entity Generic			E-G							Student is not self consistent, and the triplet can not distinguish if entity is Dep. or Indp.
OTHER			O							

* - In the version 9.1 5a took the place of 5b and vice versa.

(a) - After adaptation in the final test version, choice 1a become compatible also with non-intrusive independent entity.

~~(c)~~ - After adaptation in the final test version,, choice 4c become incompatible with non-intrusive dependent entity.

APPENDIX K-2
WALL-VACUUM CONTEXT – SUB-MODEL COMBINATIONS AND DESCRIPTIONS

Table K-1.1. Combinations and descriptions of models and sub-models in the wall-vacuum context

MODELS in Wall-Vacuum context			CODE	ANSWER COMBINATION						SUB MODEL DESCRIPTION
	Sub model 1st order effect	**Sub model 2nd order effect**		**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	
Wave	Longitudinal		W-L	b	c	b	e	d	b	Everything said for the air context with respect to this model and sub-models applies here too.
	Transversal		W-T	b	d	b	e	d	b	
	Circular		W-C	b	e	b	e	d	b	
	Phonon (L)		W-PH	e	c,e	b	e	d	b	
Intrinsic	Moving Wall (Air-Wall-Air)	Propagating Wall	I-PW	b	a,b,c,d,e	c,d	e	d	b	The intrinsic motion of the particles of the medium is traveling motion of air particles then wall particles and again air particles. The triplet can not distinguish 2^{nd} order sub-model.
		Randomly Traveling Wall	I-RTW	b	a,b,c,d,e	e	e	d	b	
		Generic Intrinsic Wall	I-GW							
	Propagating Air	With Not Affected Wall	I-PA (SW)	d	a	a	a	e	b	The intrinsic motion of the particles of the medium is traveling motion of air particles from one side of the wall to the other.
		With Not Affected Wall (2)	I-PA (SW)	d	b,c,d,e	b	a	e	b	
		With Vibrating Wall	I-PA (VW)	d	b,c,d,e	b	d	b*	b	
		With Traveling Wall	I-PA (TW)	d	a,b,c,d,e	c,d,e	d	b*	b	
		Generic Intrinsic-PA	I-PA (G)							The triplet can not distinguish 2^{nd} order sub-model.
	Generic Propagating air		PA							The triplet code for propagating air option in questions 1, 4, 5 before Q6 is "consulted" in order to associate this movement with the nature of sound (to assign a model to it).

MODELS in Wall-Vacuum context (Continued)			CODE	ANSWER COMBINATION						SUB MODEL DESCRIPTION
	Sub model 1st order effect	**Sub model 2nd order effect**		**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	
Ear-born	Propagating Air	With Not Affected Wall	EB-PA (SW)	d	a	a	a	e	c	Sound is created when particles of the medium (air) hit the listener's ear. This sensation can be caused by the air particles that travel all the way from one side of the wall to another (propagating air), or due to wave-like mechanism in which air particles on the listener's side set up the wall particles into motion and these set up the air particles on the listener's side into motion.
		With Not Affected Wall (2)	EB-PA (SW)	d	b,c,d,e	b	a	e	c	
		With Vibrating Wall	EB-PA (VW)	d	b,c,d,e	b	d	b*	c	
		With Traveling Wall	EB-PA (TW)	d	a,b,c,d,e	c,d,e	d	b*	c	
		Generic Ear-born-PA	EB-PA (G)							
	Due to the moving Wall (Air-Wall-Air)		EB-MW							
Dependent Entity	Preconditioned Motion	Vibrating Wall	DE-P (V)	c,e	c,d,e	b	c	a*	a	Because in the wall context there are two types of the medium, dependent sound entity can utilize motion of either wall particles (air-wall-air mechanism) or air particles alone (that propagate through the wall from one side to another). This section describes air-wall-air mechanism and all things said in the air context apply here too.
		Randomly Vibrating Wall	DE-P (RV)	c,e	b	b	c	a*	a	
		Propagating Wall	DE-P (P)	c,e	a,b,c,d,e	c,d	c	a*	a	
		Randomly Traveling Wall	DE-P (RT)	c,e	a,b,c,d,e	e	c	a*	a	
	Constant Motion	Vibrating Wall	DE-C (V)	c,e	c,d,e	b	a ~~(c)~~	e	a	
		Randomly Vibrating Wall	DE-C (RV)	c,e	b	b	a ~~(c)~~	e	a	
	Generic Dependent Entity		DE-G							
	Propagating Air	With Not Affected Wall	DE-PA (SW)	d	a	a	a	e	a	This section is related to mechanism in which air particles travel all the way from one side of the wall to another. Second order sub-model describes the motion of wall particles associated with traveling of the air particles through the wall.
		With Not Affected Wall (2)	DE-PA (SW)	d	b,c,d,e	b	a	e	a	
		With Vibrating Wall	DE-PA (VW)	d	b,c,d,e	b	d	b*	a	
		With Traveling Wall	DE-PA (TW)	d	a,b,c,d,e	c,d,e	d	b*	a	
		Generic Dependent Entity-PA	DE-PA							

MODELS in Wall-Vacuum context (Continued)			CODE	ANSWER COMBINATION						SUB MODEL DESCRIPTION
	Sub model 1st order effect	Sub model 2nd order effect		Q1	Q2	Q3	Q4	Q5	Q6	
Independent Entity	Shaking		IE-S	a,e	c,d,e	b	b	c	d,e	
	Randomly Shaking		IE-RS	a,e	b	b	b	c	d,e	
	Pushing		IE-P	a,e	a,b,c,d,e	c,d	b	c	d,e	Everything said for the air context with respect to this model and sub-models applies here too.
	Randomly Pushing		IE-RP	a,e	a,b,c,d,e	e	b	c	d,e	
	Non-intrusive		IE-NI	e (a)	a	a	a	e	d,e	
	Non-intrusive (2)		IE-NI	e (a)	b,c,d,e	b	a	e	d,e	
	Generic Independent Entity		IE-G							Student is not self consistent, and the triplet can not distinguish 1st order sub-model.
	With Propagating Air		IE-PA							Sound is an independent entity and when it propagates through the wall, it causes traveling of the air particles through from one side of it to another.
Entity Generic			E-G							Student is not self consistent, and the triplet can not distinguish if entity is Dependent or Independent
OTHER			O							

* - In the version 9.1 5a took the place of 5b and vice versa.
(a) - After adaptation in the final test version,, choice 1a become compatible also with non-intrusive independent entity.
~~(c)~~ - After adaptation in the final test version,, choice 4c become incompatible with non-intrusive dependent entity.

APPENDIX L
EXPLAINING MICROSOFT EXCEL® PROGRAM FOR DATA ANALYSIS

This appendix serves to expand section 4.5.3 of the dissertation by elaborating in greater detail on the functioning of programs for data analysis. The programs are written using operational functions of MS Excel and they can be found in electronic format on the CD that accompanies this dissertation. They are also available on the web (see Appendix W).

There are 10 worksheets and charts within the MS Excel file that serves as the program for analysis of the air context or for short the "air program." These worksheets and charts are listed below in the order in which they appear in the program. The function of each of them is briefly described in parentheses.

1. Analysis (contains data and performs all major analytical procedures)
2. Time Chart (displays results in terms of percentages of times at which each of the models was used)
3. Student Chart (displays results in terms of percentages of students that use any of the models at least once)
4. Movements (displays the dynamics of the medium particles answered in questions 2 and 3)
5. Model States (displays students' models states with a detailed mixed state bar)
6. Correctness (displays statistics related to the correctness of the answers
7. Sub-models (displays in a tabular form the frequency of all of the sub-models)
8. PP Data (displays data ready for pasting into PowerPoint presentation)
9. Model States (2) (displays students' models states without details in the mixed state bar)
10. Air (contains codes and corresponding models)

This order of worksheets and charts has been established keeping in mind the convenience of a typical user - an instructor or a teacher who wants to determine his or her students' mental models for a formative purpose or an action research. Details of each of these worksheets are described below and the sheets with similar functions are grouped and described together.

The program for analysis of the test pertaining to the air context (or "air program" for short) is described first. The wall context program will be described only in terms of its differences with respect to the air program.

1 Program for analysis of the air context

1.1 "Analysis" worksheet and "Air" worksheet

The "Analysis" worksheet is one in which the data needs to be entered (Columns B-G) and also one in which all major analytical operations are performed. The answers of each student are entered into the same row from column B to column G in the form of the answer choice letters – a, b, c, d or e. The program concatenates all answers (column I) given by a particular student and looks for pre-determined answer combinations in the "Air" sheet that corresponds with the probed models and their sub-model variations.

If a match is found for the answered combination, the program assigns the respective mental model code in column J of the "Analysis" sheet. If an answer combination matches no model, an "N" is assigned to the same column. If a student uses a single model (i.e. a specific combination of answers throughout all six questions in the test) - we say s/he is consistent or in a pure model state. Models that these students use are determined in column "J." If a student uses a combination of answers throughout the test that does not correspond to any of tested models, s/he is inconsistent or in a mixed model state. These students do not use a single model, so for them it is necessary to determine the models that they mix, if any. This is accomplished by eliciting models that a students uses in each of the model determining question triplets. These triplets are formed from question combinations of Q1-Q2-Q3; Q2-Q3-Q4; Q2-Q3-Q5; Q2-Q3-Q6. Questions Q2 and Q3 together determine how air particles move while the sound propagates through the air according to the student. The remaining question in each of these triplets determines the student's rationale for this movement. The programming logic of determining the model associated with a triplet is identical to the logic of finding a model corresponding to all six questions. Respective answers are concatenated in columns L, N, P and R and then compared to the respective combinations in the Air sheet (columns C, E, G and I). If a match is found, the corresponding model is assigned next to each of the triplet combinations in the analysis sheet. Otherwise an "O", which stands for "Other," is assigned to a triplet. In the case of consistent students – their models are assigned to all triplet combinations directly so each triplet is assigned the same model.

A major portion of the analysis is performed in rows 1-35 and columns AD-AQ of the "Analysis" worksheet. In column AH the number of times that each of the models is consistently used is summed. The frequency at which models and model triplets are used is summed up also in rows 2005-2033 and columns J, M, O, Q and S. Results in rows 2005-2033 are used (in column AL) to determine the total number of triplets in which each model was used. In columns AH and AL the program determines the number of triplets in which models were consistently used (number of consistent students using that model multiplied by four) or inconsistently used (total number of triplets minus the consistent contribution).

The number of students that use each of the sub-models at least once is calculated indirectly in columns CS-DU (for each of the sub-models separately) and in columns CD-CL (where sub-models are flocked together under their respective major models).

The frequency of different motions of the particles of the medium is also determined separately from the models in column "U" of the Analysis sheet and based on the concatenated answer combination in column T. A template combination for movements are in columns K and L of the "Air" sheet.

Columns EH-EO serve to determine the correctness of the answers. Finally, in columns ES-FF additional analysis is performed in order to determine the number of students who are in a mixed model state but who mix only Independent and Dependent Models. The number of students who are in the mixed model state and mix only the Wave and Ear-born Model are found in columns FH-FQ.

1.2 "Time" chart and "Students" chart

These two charts display results in terms of the frequency at which students use each of the models from two different perspectives. The time chart shows the model distribution in an absolute sense, i.e. the sum of all percentages showing usage of each of the models in this chart adds up to 100%. The Students chart on the other hand shows the percentages of students that use each of the models at least once. Both of these perspectives are informative ways of looking into how models are distributed within the sample. Both charts distinguish contributions to model usage that come from consistent and inconsistent students.

1.3 "Movements" chart

This chart displays the dynamics of the medium particles determined in questions 2 and 3. The sum of the percentages in the diagram adds up to 100%. Different vibrations are shown on the horizontal axis and traveling of the particles associated with any of the vibrations are displayed on top of each other in the same column.

1.4 "Model States" charts

Two charts display students' model states (charts "Model States" and "Model states (2)"). Each of them has two bar columns. The left bar displays students in the pure model state and the right one displays students in the mixed model state. The bar related to the pure model state in these diagrams shows students who consistently use Wave Models (Longitudinal, Transversal and Circular) and those that consistently use any other model separately. The difference between the charts is in the way in which they represent mixed model states. Chart "Model States 2" displays students in a mixed model state in a uniform bar and the other chart sorts out students that mix exclusively (a) Dependent and Independent Entity Models (b) those who mix exclusively Wave and Ear-born Models and (c) students that use any other model combination.

1.5 "Sub-models" worksheet

The worksheet "Sub-models" contains a table that shows detailed results related to all sub-models.

1.6 "Correct" worksheet

This worksheet displays statistics related to the correctness of answers in tabular and graphic form.

1.7 "PP Data" worksheet

Data in this sheet are ready to be exported into MS PowerPoint and MS Excel templates for presentation of findings (see Appendix U). Results needed for presentation of findings are compiled in this worksheet. Because files for data analysis are large, once the results are calculated it is convenient to copy and store them using the templates provided in folder 5 on the dissertation CD (see Appendix U). Sheets provided for the storage of results are in the MS Excel file called "Model template 9.2." Sheets in this file into which the results should be copied have the same cell organization as the "PP Data" sheet in the Model Analysis program so that cutting and pasting the data is an easy procedure. The MS PowerPoint file "Model template 9.2" can also be found on the dissertation CD. It contains the same charts which the "Analysis" program contains so that a user can easily represent the graphs with PowerPoint by cutting and pasting the resulting data into respective charts.

2 Program for analysis of the wall context

The analysis sheet of the analysis program related to the wall context performs all of the functions that the air program does in addition to several others. This is because the wall context involves three sorts of "identifiable kinds of things" when sound propagation is concerned and these are sound, air particles and wall particles. This complicates the analysis of the wall context with respect to the air context because only two things were involved in models related to air context (sound and air particles). This problem reflected in the analysis of the wall test in the way that sometimes more than three questions were needed in order to determine the model in a particular question triplet.

2.1 Issue of the medium in answers to question 6

Question 6 (vacuum context) combined with the wall context leaves the question open if sound propagation is associated with propagation of the air particles so they move all the way from the speaker to the listener (i.e. they pass through the wall) or if it is a movement of one medium at the time (air-wall-air) that is associated with the sound propagation.

For example, if a student picks a choice related to the Dependent Entity Model in question 6, it is not clear if the propagation of the sound entity depends on the motion of the air through the wall or if it is the motion of the wall particles that carry the sound through the wall.

This was a problem with the Intrinsic Model (choice 6b), Dependent Entity (6a) and Ear-born Model (6c). This was not an issue with the Independent Entity Model (6d, 6e) because propagation of an independent entity does not depend on (any) medium.

The problem with the Intrinsic and Dependent models was solved in a way that will be explained during the example of the Intrinsic Model: In each of questions 1, 4 and 5, a student could choose between the option corresponding to the Intrinsic/Wave Models (which in the wall context pertains to the movement of the wall particles) and the choice corresponding to the Propagating Air Model. So, to determine which medium a student refers to in question 6, questions 1, 4 and 5 had to be "consulted." In the program, the wall was set as a default medium, but if student picked a propagating air choice in questions 1, 4, or 5 more times than the intrinsic choice, then the model was reassigned to the Propagating Air Model. These calculations are performed in columns GH-HE in the wall analysis program. Columns GH-GX serve to count the number of instances in which propagating air was used and columns GY-HE serve to determine the medium associated with answers 6a (dependent) and 6b (intrinsic).

The problem of assigning the medium to an intrinsic group of models (Wave and Intrinsic Models) and Dependent Entity Model was solved in this way because in each of questions 1, 4, and 5, a student could choose between options pertaining to either of these models and the Propagation Air Model. This procedure was not applicable to the Ear-born model because a choice related to it is offered in the wall context for the first time in question 6. Therefore, the problem of determining the medium associated with the Ear-born Model (choice 6c) was solved in a way that the air was set as a default medium, i.e.

propagating air as a default mechanism (because it is air and not wall particles that can hit our ear). But, this default option makes sense only if propagating air choice was picked at least once in questions 1, 4 or 5. So, the program determines if this was the case. If yes, propagating air is the mechanism. If not then the air-wall-air exchange of the medium is involved (code EB-MW) unless a student said in question 3 that wall particles do not move at all (and also never picked propagating air choice). If this is the case (probed in column HH, Analysis worksheet), then the choice 6c (Ear-born choice) is assigned to the category "other," i.e. we do not know which model is associated with choice 6c.

2.2 Issue of the model related to propagating air choices in questions 1, 4 and 5.
An opposite problem of the one with question 6 existed in cases where a student was not self-consistent and the answer in any of questions 1, 4, or 5 (of the wall context) was propagating air choice. This answer together with a movement of the wall particles in questions 2 and 3 reveals nothing about how this movement is related to the sound. To determine this, the answer given to question 6 had to be checked out, which then determined the relationship of the propagating air and the sound propagation. Calculations related to this are in columns HK-HO.

2.3 Issue of the model related to constant motion choices in questions 4 and 5.
Each of questions 4 and 5 have a choice that states that the motion of the wall particles is not affected by the sound propagation. These choices also do not reveal the model of sound propagation and question 6 was consulted in these cases to determine the model associated with the propagating air choice (in the same way as described in section 2.2 of this Appendix). These particular calculations are in columns HQ-HW.

It is important to mention the difference between the Intrinsic group of models and the Ear-born Model on one side and the Entity Models on another side with respect to the constant motion of the particles of the medium. Namely, it is illogical that ear-born sound is assigned to a student that says that wall particles move all the time the same way (with or without sound) and who also never picks the propagating air option in questions Q1, Q4 or Q5 (while the speaker speaks). In that case, everything that moves will move all the time in the same way and there is nothing that can cause the sound at a particular moment. A similar problem exists with respect to the Intrinsic Model. If everything moves all the time in the same way and (according to intrinsic choice) sound *is* this motion then the same sound exists all the time.

Therefore, the rationale that wall particles move all the time in the same way and air does not propagate through the wall context can be associated only with the Dependent and Independent Entity Models. Thus, if the described dynamics of the wall and air particles is associated with the Ear-born or Intrinsic Model this triplet is categorized as "other," i.e. no model is assigned to it.

APPENDIX L-1
RANDOM MODEL DISRIBUTION IN TWO CONTEXTS

Answer choices shown in Appendices K-1 and K-2 together with the analysis algorithm described in section 4.5.3 and in Appendix L define a random distribution of models in the FAMM-Sound tests. While interpreting the test, it is useful to be familiar with these random distributions. The table below shows a random distribution of models in the air context and is accompanied by a figure that displays those models graphically.

Table L-1.1
Random distribution of models in the air context

AIR RANDOM	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dep. Entity	Indep. Entity	Other
Consistently	0.01	0.01	0.10	0.12	0.29	0.61	20.93
Inconsistently	0.79	1.59	11.90	15.08	14.97	24.92	8.67
Total	0.80	1.60	12.00	15.20	15.26	25.54	29.60

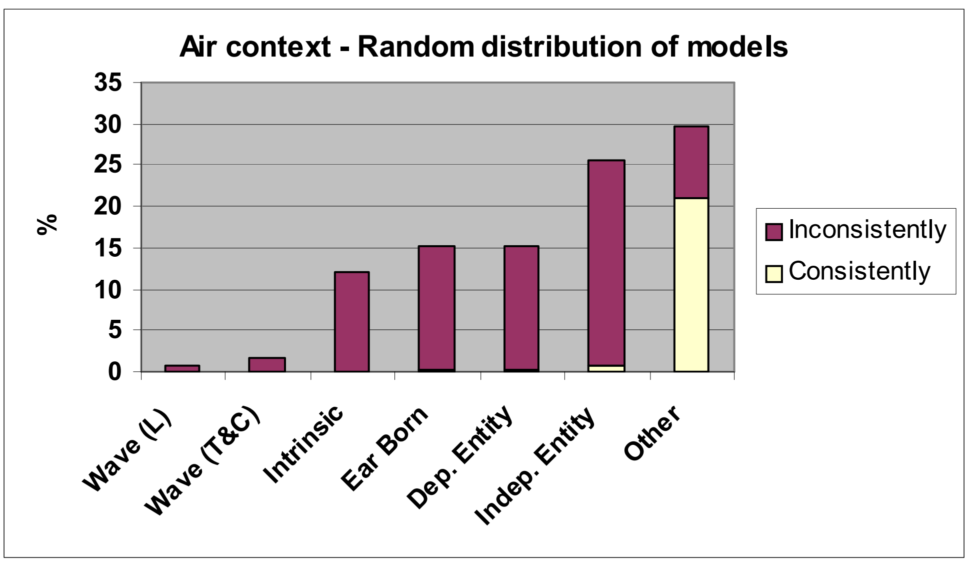


Figure L-1.1
A graphical representation of random distribution of the models in the air context

Table L-1.2
A random distribution of models in the air context

WALL RANDOM	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dep. Entity	Indep. Entity	Other
Consistently	0.02	0.01	0.25	0.15	0.45	0.61	20.15
Inconsistently	0.72	1.45	18.48	6.37	13.91	28.34	9.07
Total	0.74	1.47	18.72	6.52	14.36	28.96	29.23

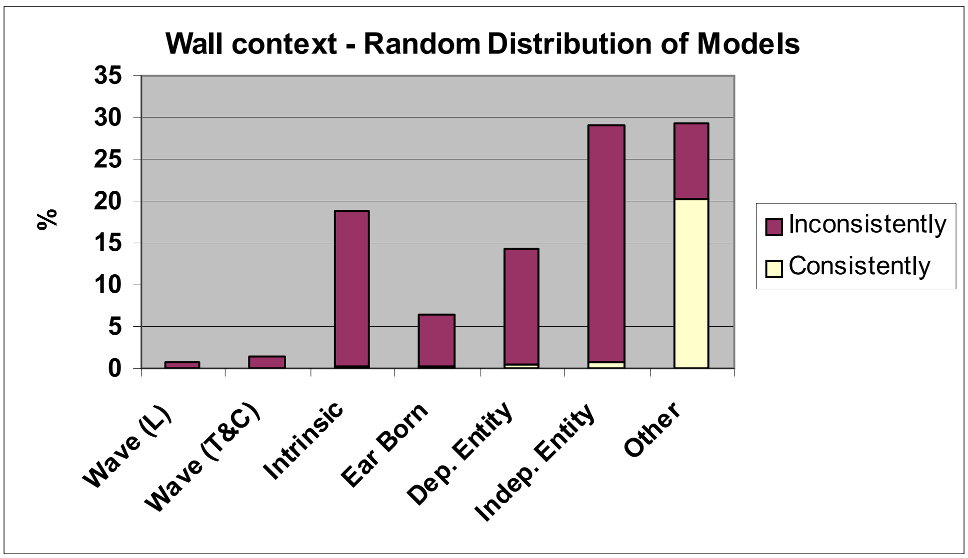


Figure L-1.2
A graphical representation of random distribution of models in the wall context

Sources of differences between random distributions of models in the air and wall contexts

The random model distributions in the air and wall contexts of the test are not identical. The differences are described and explained below:

1) The probability for random consistent usage of the Longitudinal Wave Model is higher in the wall context because phonon combination in the wall context includes not only longitudinal but also circular motion. This is because the wall is solid and unlike air it supports shear. So, in order not to raise any issues about relative directions (of the vibration of wall particles and sound propagation) circular motion was included in the Phonon Model of the wall context.
2) The probability for random inconsistent usage of the Longitudinal Wave Model is lower in the wall context because of the way in which triplets associated with question 6 are analyzed in the wall context (see Appendix L). Although the triplet in Q2, Q3 and Q6 may be a Longitudinal Wave Model, if a propagating air option was

used in questions 1, 4 and 5, then this triplet is projected into the Intrinsic Model (propagating air sub-model).

3) The probability for random inconsistent usage of Transversal and Circular Wave Models is lower in the wall context because of the same reason explained for the Longitudinal Wave Model (point 2). Consistent usage of Transversal and Circular Wave Models is the same in both contexts because the Phonon Model was not associated with those models.
4) The probability for a random (either consistent or inconsistent) occurrence of the Intrinsic Model is higher in the wall context because in the wall context motion of air and wall particles may be associated with this model (not just motion of air particles as in the air context). The sum of the Wave and Intrinsic Models in air context is 14.40% and in the wall context it is 21.04%. These percentages obtained in real data are much closer (see section 5.4.3.).
5) The Ear-born Model and Dependent Entity Model have higher chances to be consistently used in the wall context because full answer combinations consistent with both of them may be associated with air-wall-air dynamics and also with propagating air dynamics.
6) Unlike the case of dependent entity, the chances that the Ear-born Model will be used inconsistently are much smaller in the wall context than in the air context. This is because in the wall context the Ear-born choice is offered only in question 6 and in the air context it is offered in Q1, Q4, Q5 and Q6. However, the difference is not four-fold because if a student picked the Ear-born Model in question 6 the propagating air option in questions Q1, Q4, Q5 is associated with that model.
7) The random consistent usage of the Independent Entity Model does not depend on the medium and so it does not depend on the context. The Independent Entity Model in total has a greater chances to be "selected" than other models because in question 6 there are two choices that say "Yes, sound propagates through the vacuum," and both of these correspond to the independent entity, while the other models have only one choice associated with them.

Chances of getting a consistent model randomly in different contexts and different tests

Table L-1.3 shows the chances of getting a consistent model randomly in these tests.

Table L-1.3
The random distribution of models in the air context

Context	Test Version	Chance of getting a consistent model randomly
Air	Full version (6 questions)	0.01152 or 1 in 86.81 (128 in 15625)
Wall	Full version (6 questions)	0.01491 or 1 in 67.06 (233 in 15625)
Air	Q1234	0.1269 or 1 in 8 (128 in 1024)
Air	Q2356	0.1054 or 1 in 9.48 (108 in 1024)

APPENDIX M
RESULTS RELATED TO MODEL DISTRIBUTION AND STUDENTS' CONSISTENCY

For all tables in this appendix the following notation applies:

* Results with Incompatible samples included
** Samples are incompatible with others because they are smaller than 15 students.
*** Post-instruction samples are incompatible with others because no regular intervention was made to address the topic of the test.

Table M.1
Results for pre-instruction tests in air context

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
TERTIARY LEVEL			**Air**	**Pre**										
University, NY	Spring 03	Calculus	Air	Pre	100	23.00	9.00	9.50	8.00	20.75	19.25	17.00	20.25	4.25
University, PA**	Spring 03	Algebra	Air	Pre	6	0.00	0.00	0.00	8.33	12.50	20.83	12.50	45.83	0.00
University, NC	Fall 03	Calculus	Air	Pre	57	7.02	1.75	0.44	5.70	26.32	10.96	20.18	30.70	5.70
University, KS	Fall 03	Algebra	Air	Pre	99	12.12	2.02	2.02	2.53	21.72	19.70	17.68	32.58	2.78
Weighted Average*					262	14.89	4.58	4.48	5.44	22.14	17.65	17.84	27.77	3.91
Simple Avg.*						10.53	3.19	2.99	6.14	20.32	17.69	16.84	32.34	3.18
SD of Simple Avg.*						9.68	3.97	4.43	2.68	5.75	4.53	3.20	10.50	2.43
Weighted Average					257	15.23	4.69	4.59	5.37	22.36	17.58	17.97	27.34	4.00
Simple Avg.						**14.05**	**4.26**	**3.99**	**5.41**	**22.93**	**16.64**	**18.28**	**27.84**	**4.24**
SD of Simple Avg.						8.16	4.11	4.84	2.75	2.97	4.92	1.67	6.64	1.46
SECONDARY LEV.			**Air**	**Pre**										
High S. (1), HR	Fall 03	Algebra	Air	Pre	28	**7.14**	**0.00**	**0.89**	**5.36**	**13.39**	**14.29**	**28.57**	**26.79**	**10.71**

Table M.2
Results for pre-instruction tests in wall context

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
TERTIARY LEVEL			**Wall**	**Pre**										
University, PA**	Spring 03	Algebra	Wall	Pre	6	0.00	0.00	0.00	0.00	0.00	16.67	25.00	54.17	4.17
University, KS	Fall 03	Algebra	Wall	Pre	76	**14.47**	**3.95**	**3.29**	**6.91**	**12.83**	**6.25**	**23.03**	**43.09**	**4.61**
Weighted Average*					82	13.41	3.66	3.05	6.40	11.89	7.01	23.17	43.90	4.57
Simple Avg.*						7.24	1.97	1.64	3.45	6.41	11.46	24.01	48.63	4.39
SD of Simple Avg.*						10.23	2.79	2.33	4.88	9.07	7.37	1.40	7.83	0.31
SECONDARY LEV.			**Wall**	**Pre**										
High S. (1), HR	Fall 03	Algebra	Wall	Pre	21	**14.29**	**0.00**	**0.00**	**1.19**	**23.81**	**7.14**	**21.43**	**26.19**	**20.24**

Table M.3
Results for pre-instruction tests in both contexts

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
TERTIARY LEVEL			**Both**	**Pre**										
University, PA**	Spring 03	Algebra	Both	Pre	12	0.00	0.00	0.00	4.17	6.25	18.75	18.75	50.00	2.08
University, KS	Fall 03	Algebra	Both	Pre	175	**13.14**	**2.86**	**2.57**	**4.43**	**17.86**	**13.86**	**20.00**	**37.14**	**3.57**
Weighted Average*					187	12.30	2.67	2.41	4.41	17.11	14.17	19.92	37.97	3.48
Simple Average*						6.57	1.43	1.29	4.30	12.05	16.30	19.38	43.57	2.83
SD of Simple Avg.*						9.29	2.02	1.82	0.19	8.21	3.46	0.88	9.09	1.05
SECONDARY LEV.			**Both**	**Pre**										
High S. (1), HR	Fall 03	Algebra	Both	Pre	49	**10.20**	**0.00**	**0.51**	**3.57**	**17.86**	**11.22**	**25.51**	**26.53**	**14.80**

Table M.4
Results for post-instruction tests in air context – tertiary level

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
TERTIARY LEVEL			**Air**	**Post**										
University, NY****	Spring 04	Calculus	Air	Mid	96	33.33	20.83	27.60	4.95	22.14	9.64	16.15	17.97	1.56
University, NY	Spring 05	Calculus	Air	Post	95	36.84	23.16	29.21	4.47	22.37	4.21	16.32	20.26	3.16
University, PA**	Spring 04	Algebra	Air	Post	6	33.33	16.67	20.83	4.17	12.50	16.67	16.67	29.17	0.00
University, KS	Spring 03	Calculus	Air	Post	69	23.53	11.76	11.40	9.19	25.37	15.81	15.07	18.75	4.41
University, KS	Spring 03	Algebra	Air	Post	107	16.82	8.41	7.01	9.58	19.86	19.39	16.36	22.90	4.91
University, KS	Spring 03	Concepts	Air	Post	33	0.15	0.03	4.55	3.03	27.27	3.79	21.97	36.36	3.03
University, NC	Fall 04	Calculus	Air	Post	19	5.26	5.26	9.21	9.21	11.84	14.47	32.89	22.37	0.00
University, HR	Fall 03	Calculus	Air	Post	29	6.90	3.45	2.59	8.62	17.24	21.55	8.62	25.86	15.52
University, KS***	Fall 03	Algebra	Air	Post	98	20.41	3.06	4.59	4.85	22.70	22.96	13.27	28.32	3.32
University, KS	Fall 03	Concepts	Air	Post	96	14.58	2.08	4.17	1.56	26.04	13.54	16.93	34.64	3.13
University, KS	Fall 03	Concepts	Air	Post	105	15.24	1.90	2.14	2.62	17.86	17.38	15.48	39.29	5.24
University, KS	Fall 03	Concepts	Air	Post	78	2.56	1.28	2.56	1.28	24.36	16.67	22.44	28.85	3.85
University, IL	Fall 03	Concepts	Air	Post	20	15.00	0.00	0.00	0.00	35.00	17.50	21.25	25.00	1.25
University, LA	Fall 03	Concepts	Air	Post	19	26.32	10.53	14.47	2.63	13.16	14.47	14.47	34.21	6.58
C. College, KS	Spring 03	Concepts	Air	Post	19	0.00	0.00	0.00	0.00	13.16	6.58	34.21	39.47	6.58
Weighted Average*					889	18.70	8.11	10.16	4.68	21.96	14.67	17.14	27.36	4.03
Simple Avg.*						16.69	7.23	9.36	4.41	20.72	14.31	18.81	28.23	4.17
SD of Simple Avg.*						12.25	7.76	9.59	3.34	6.55	5.86	6.92	7.22	3.75
Weighted Average					689	16.30	6.99	8.43	4.62	21.92	14.17	17.84	28.51	4.51
Simple Avg.						**13.60**	**5.66**	**7.28**	**4.35**	**21.13**	**13.78**	**19.67**	**29.00**	**4.80**
SD of Simple Avg.						11.36	6.89	8.24	3.76	6.91	5.84	7.50	7.49	3.89

**** Samples incompatible with others because data was taken in the middle of the instruction (in addition to before and after it).

Table M.5
Results for post-instruction tests in air context – secondary and primary level

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
SECONDARY LEV.			**Air**	**Post**										
High S., KS	Spring 03	Concepts	Air	Post	82	8.54	1.22	1.52	1.83	20.43	15.24	21.04	30.79	9.15
High S., MN	Spring 03	Concepts	Air	Post	23	21.74	0.00	8.70	0.00	15.22	13.04	21.74	34.78	6.52
High S. (1,2), HR	Spring 03	Algebra	Air	Post	51	13.73	3.92	3.92	4.41	12.25	20.59	17.65	32.35	8.82
High S. (1), HR***	Fall 04	Algebra	Air	Post	28	17.86	7.14	16.07	3.57	14.29	21.43	14.29	26.79	3.57
High S. (2), HR***	Fall 03	Algebra	Air	Post	24	33.33	20.83	38.54	0.00	7.29	19.79	15.63	14.58	4.17
Weighted Average*					208	15.38	4.81	9.13	2.28	15.50	17.67	18.75	29.21	7.45
Simple Avg.*						19.04	6.62	13.75	1.96	13.90	18.02	18.07	27.86	6.45
SD of Simple Avg.*						9.37	8.40	14.93	2.02	4.77	3.67	3.27	7.97	2.57
Weighted Average					156	12.18	1.92	3.37	2.40	16.99	16.67	20.03	31.89	8.65
Simple Avg.						**14.67**	**1.71**	**4.71**	**2.08**	**15.97**	**16.29**	**20.14**	**32.64**	**8.16**
SD of Simple Avg.						6.65	2.01	3.65	2.22	4.14	3.88	2.19	2.01	1.43
PRIMARY LEVEL			**Air**	**Post**										
Middle S. (1), HR	Spring 03	Algebra	Air	Post	20	20.00	0.00	0.00	0.00	15.00	45.00	21.25	13.75	5.00
Middle S. (2), HR	Spring 03	Algebra	Air	Post	44	2.27	0.00	0.00	0.00	12.50	28.98	23.30	26.70	8.52
Weighted Average					64	7.81	0.00	0.00	0.00	13.28	33.98	22.66	22.66	7.42
Simple Avg.						**11.14**	**0.00**	**0.00**	**0.00**	**13.75**	**36.99**	**22.27**	**20.23**	**6.76**
SD of Simple Avg.						12.54	0.00	0.00	0.00	1.77	11.33	1.45	9.16	2.49

Table M.6
Results for post-instruction tests in wall context – tertiary level

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
TERTIARY LEVEL			**Wall**	**Post**										
University, PA**	Spring 04	Algebra	Wall	Post	4	25.00	0.00	0.00	0.00	25.00	0.00	25.00	50.00	0.00
University, KS	Spring 03	Calculus	Wall	Post	58	25.86	18.97	21.12	13.36	17.24	0.86	23.28	18.53	5.60
University, KS	Spring 03	Algebra	Wall	Post	100	14.00	3.00	5.50	4.25	17.50	9.00	25.25	32.00	6.50
University, KS**	Spring 03	Concepts	Wall	Post	5	0.20	0.00	0.00	0.00	55.00	5.00	10.00	30.00	0.00
University, HR	Fall 03	Calculus	Wall	Post	31	3.23	0.00	6.45	10.48	34.68	1.61	16.13	12.90	17.74
University, KS*	Fall 03	Algebra	Wall	Post	79	30.38	13.92	7.28	11.71	21.52	5.06	18.99	32.59	2.85
University, IL	Fall 03	Concepts	Wall	Post	33	15.15	3.03	3.03	1.52	20.45	3.79	26.52	37.88	6.82
University, LA	Fall 03	Concepts	Wall	Post	18	5.56	0.00	0.00	12.50	12.50	0.00	23.61	50.00	1.39
C. College, KS	Spring 03	Concepts	Wall	Post	19	0.00	0.00	0.00	2.63	9.21	0.00	36.84	44.74	6.58
Weighted Average*					347	17.58	7.49	7.64	8.00	20.10	4.47	23.13	30.55	6.12
Simple Avg.*						13.26	4.32	4.82	6.27	23.68	2.81	22.85	34.29	5.28
SD of Simple Avg.*						11.73	7.10	6.81	5.65	13.84	3.12	7.46	12.98	5.45
Weighted Average					259	13.90	5.79	8.01	7.14	18.92	4.34	24.61	29.63	7.34
Simple Avg.						**10.63**	**4.17**	**6.02**	**7.46**	**18.60**	**2.54**	**25.27**	**32.68**	**7.44**
SD of Simple Avg.						9.56	7.40	7.87	5.26	8.84	3.46	6.72	14.59	5.44

Table M.7
Results for post-instruction tests in wall context – secondary and primary level

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
SECONDARY LEV.			**Wall**	**Post**										
High S., KS	Spring 03	Concepts	Wall	Post	20	15.00	5.00	12.50	3.75	17.50	10.00	25.00	30.00	1.25
High S., MN	Spring 03	Concepts	Wall	Post	24	12.50	8.33	7.29	8.33	13.54	6.25	19.79	29.17	15.63
High S. (1,2), HR	Spring 03	Algebra	Wall	Post	51	17.65	3.92	3.92	7.35	13.24	8.33	23.53	30.88	12.75
High S. (1), HR***	Fall 04	Algebra	Wall	Post	23	8.70	0.00	6.52	6.52	9.78	16.30	23.91	31.52	5.43
High S. (2), HR***	Fall 03	Algebra	Wall	Post	27	25.93	14.81	33.33	0.00	21.30	6.48	21.30	13.89	3.70
Weighted Average*					145	16.55	6.21	11.55	5.52	14.83	9.14	22.76	27.41	8.79
Simple Avg.*						15.95	6.41	12.71	5.19	15.07	9.47	22.71	27.09	7.75
SD of Simple Avg.*						6.48	5.56	11.94	3.37	4.43	4.11	2.11	7.43	6.14
Weighted Average					95	15.79	5.26	6.58	6.84	14.21	8.16	22.89	30.26	11.05
Simple Avg.						**15.05**	**5.75**	**7.90**	**6.48**	**14.76**	**8.19**	**22.77**	**30.02**	**9.87**
SD of Simple Avg.						2.57	2.30	4.32	2.41	2.38	1.88	2.69	0.86	7.61
PRIMARY LEVEL			**Wall**	**Post**										
Middle S. (1), HR	Spring 03	Algebra	Wall	Post	22	9.09	9.09	0.00	19.32	17.05	1.14	34.09	19.32	9.09
Middle S. (2), HR	Spring 03	Algebra	Wall	Post	46	6.52	0.00	0.54	1.09	11.41	7.07	28.26	40.22	11.41
Weighted Average					68	7.35	2.94	0.37	6.99	13.24	5.15	30.15	33.46	10.66
Simple Avg.						**7.81**	**4.55**	**0.27**	**10.20**	**14.23**	**4.10**	**31.18**	**29.77**	**10.25**
SD of Simple Avg.						1.82	6.43	0.38	12.89	3.98	4.19	4.12	14.78	1.64

Table M.8
Results for post-instruction tests in both (air and wall) contexts – tertiary level

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
TERTIARY LEVEL			**Both**	**Post**										
University, PA**	Spring 04	Algebra	Both	Post	10	30.00	10.00	12.50	2.50	17.50	10.00	20.00	37.50	0.00
University, KS	Spring 03	Calculus	Both	Post	126	24.60	15.08	15.87	11.11	21.63	8.93	18.85	18.65	4.96
University, KS	Spring 03	Algebra	Both	Post	207	15.46	5.80	6.28	7.00	18.72	14.37	20.65	27.29	5.68
University, KS	Spring 03	Concepts	Both	Post	38	0.16	0.03	3.95	2.63	30.92	3.95	20.39	35.53	2.63
University, HR	Fall 03	Calculus	Both	Post	60	5.00	1.67	4.58	9.58	26.25	11.25	12.50	19.17	16.67
University, KS***	Fall 03	Algebra	Both	Post	177	24.86	7.91	5.79	7.91	22.18	14.97	15.82	30.23	3.11
University, IL	Fall 03	Concepts	Both	Post	53	15.09	1.89	1.89	0.94	25.94	8.96	24.53	33.02	4.72
University, LA	Fall 03	Concepts	Both	Post	37	16.22	5.41	7.43	7.43	12.84	7.43	18.92	41.89	4.05
C. College, KS	Spring 03	Concepts	Both	Post	38	0.00	0.00	0.00	1.32	11.18	3.29	35.53	42.11	6.58
Weighted Average*					746	17.03	6.70	7.04	7.14	21.08	11.46	19.47	28.32	5.50
Simple Avg.*						14.60	5.31	6.48	5.60	20.80	9.24	20.80	31.71	5.38
SD of Simple Avg.*						10.95	5.07	4.99	3.80	6.44	4.04	6.45	8.74	4.65
Weighted Average					559	14.32	6.26	7.33	6.98	20.80	10.38	20.62	27.55	6.35
Simple Avg.						**10.93**	**4.27**	**5.71**	**5.72**	**21.07**	**8.31**	**21.62**	**31.09**	**6.47**
SD of Simple Avg.						9.34	5.31	5.13	4.09	7.29	3.90	7.10	9.77	4.66

Table M.8
Results for post-instruction tests in both (air and wall) contexts – secondary and primary level

Institution	Semester	Course Math Level	Context	Pre / Post	N	Consistent (Pure model state)	Consistent Wave	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dependent Entity	Independent Entity	Other
SECONDARY LEV.			**Both**	**Post**										
High S., KS	Spring 03	Concepts	Both	Post	102	9.80	1.96	3.68	2.21	19.85	14.22	21.81	30.64	7.60
High S., MN	Spring 03	Concepts	Both	Post	47	17.02	4.26	7.98	4.26	14.36	9.57	20.74	31.91	11.17
High S. (1,2), HR	Spring 03	Algebra	Both	Post	102	15.69	3.92	3.92	5.88	12.75	14.46	20.59	31.62	10.78
High S. (1), HR***	Fall 04	Algebra	Both	Post	51	13.73	3.92	11.76	4.90	12.25	19.12	18.63	28.92	4.41
High S. (2), HR***	Fall 03	Algebra	Both	Post	51	29.41	17.65	35.78	0.00	14.71	12.75	18.63	14.22	3.92
Weighted Average*					353	15.86	5.38	10.13	3.61	15.23	14.16	20.40	28.47	8.00
Simple Avg.*						17.13	6.34	12.63	3.45	14.78	14.02	20.08	27.46	7.58
SD of Simple Avg.*						8.35	6.38	13.37	2.35	3.02	3.45	1.41	7.50	3.41
Weighted Average					251	13.55	3.19	4.58	4.08	15.94	13.45	21.12	31.27	9.56
Simple Avg.						**14.17**	**3.38**	**5.19**	**4.11**	**15.65**	**12.75**	**21.05**	**31.39**	**9.85**
SD of Simple Avg.						3.84	1.24	2.42	1.84	3.73	2.75	0.67	0.67	1.96
PRIMARY LEVEL			**Both**	**Post**										
Middle S. (1), HR	Spring 03	Algebra	Both	Post	42	14.29	4.76	0.00	10.12	16.07	22.02	27.98	16.67	7.14
Middle S. (2), HR	Spring 03	Algebra	Both	Post	90	4.44	0.00	0.28	0.56	11.94	17.78	25.83	33.61	10.00
Weighted Average					132	7.58	1.52	0.19	3.60	13.26	19.13	26.52	28.22	9.09
Simple Avg.						**9.37**	**2.38**	**0.14**	**5.34**	**14.01**	**19.90**	**26.90**	**25.14**	**8.57**
SD of Simple Avg.						6.96	3.37	0.20	6.76	2.92	3.00	1.52	11.98	2.02

APPENDIX M-1
COMPARISON OF RESULTS RELATED TO MODEL DISTRIBUTION WITH RANDOM DISTRIBUTION OF MODELS

Table M-1.1
Comparison of random model distribution and model distribution obtained from different levels in air context

AIR RANDOM	**N=15625**	**Wave (L)**	**Wave (T&C)**	**Intrinsic**	**Ear Born**	**Dep. Entity**	**Indep. Entity**	**Other**
%	Consistently	0.01	0.01	0.10	0.12	0.29	0.61	20.93
	Inconsistently	0.79	1.59	11.90	15.08	14.97	24.92	8.67
	Total	0.80	1.60	12.00	15.20	15.26	25.54	29.60

AIR COLLEGES	N=1132	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dep. Entity	Indep. Entity	Other
%	Consistently	5.65	1.86	5.39	0.00	0.35	1.77	1.06
	Inconsistently	3.36	3.14	16.74	12.68	19.63	25.51	2.87
	Total	9.01	4.99	22.13	12.68	19.99	27.27	3.93
Factor with respect to random	Consistently	441.70	144.93	56.13	0.00	1.20	2.88	0.05
	Inconsistently	4.26	1.98	1.41	0.84	1.31	1.02	0.33
	Total	11.24	3.12	1.84	0.83	1.31	1.07	0.13

AIR HS	N=226	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dep. Entity	Indep. Entity	Other
%	Consistently	3.81	0.42	2.54	0.00	0.42	2.97	3.81
	Inconsistently	4.34	2.22	12.71	15.36	21.19	26.38	3.81
	Total	8.16	2.65	15.25	15.36	21.61	29.34	7.63
Factor with respect to random	Consistently	297.93	33.10	26.48	0.00	1.44	4.83	0.18
	Inconsistently	5.51	1.40	1.07	1.02	1.42	1.06	0.44
	Total	10.18	1.66	1.27	1.01	1.42	1.15	0.26

AIR MS	N=64	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dep. Entity	Indep. Entity	Other
%	Consistently	0.00	0.00	0.00	1.56	1.56	0.00	3.13
	Inconsistently	0.00	0.00	13.28	26.17	27.73	22.27	4.30
	Total	0.00	0.00	13.28	27.73	29.30	22.27	7.42
Factor with respect to random	Consistently	0.00	0.00	0.00	12.85	5.31	0.00	0.15
	Inconsistently	0.00	0.00	1.12	1.74	1.85	0.89	0.50
	Total	0.00	0.00	1.11	1.82	1.92	0.87	0.25

Table M-1.2

Comparison of random model distribution and model distribution obtained from different levels in wall context

WALL RANDOM	**N=15625**	**Wave (L)**	**Wave (T&C)**	**Intrinsic**	**Ear Born**	**Dep. Entity**	**Indep. Entity**	**Other**
%	Consistently	0.02	0.01	0.25	0.15	0.45	0.61	20.15
	Inconsistently	0.72	1.45	18.48	6.37	13.91	28.34	9.07
	Total	0.74	1.47	18.72	6.52	14.36	28.96	29.23

WALL COLLEGES	N=429	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dep. Entity	Indep. Entity	Other
%	Consistently	3.73	3.03	2.33	0.00	1.17	3.50	2.33
	Inconsistently	3.15	4.84	16.96	4.95	21.10	29.60	3.32
	Total	6.88	7.87	19.29	4.95	22.26	33.10	5.65
Factor with respect to random	Consistently	194.25	236.74	9.34	0.00	2.60	5.69	0.12
	Inconsistently	4.34	3.33	0.92	0.78	1.52	1.04	0.37
	Total	9.24	5.36	1.03	0.76	1.55	1.14	0.19

WALL HS	N=166	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dep. Entity	Indep. Entity	Other
%	Consistently	4.82	0.60	3.61	0.60	1.20	2.41	6.02
	Inconsistently	5.42	4.22	14.16	7.83	20.63	25.00	3.46
	Total	10.24	4.82	17.77	8.43	21.84	27.41	9.49
Factor with respect to random	Consistently	251.00	47.06	14.48	3.92	2.69	3.92	0.30
	Inconsistently	7.48	2.90	0.77	1.23	1.48	0.88	0.38
	Total	13.76	3.28	0.95	1.29	1.52	0.95	0.32

WALL MS	N=68	Wave (L)	Wave (T&C)	Intrinsic	Ear-born	Dep. Entity	Indep. Entity	Other
%	Consistently	0.00	2.94	0.00	0.00	1.47	2.94	10.29
	Inconsistently	0.37	4.04	13.60	5.15	28.31	30.51	0.37
	Total	0.37	6.99	13.60	5.15	29.78	33.46	10.66
Factor with respect to random	Consistently	0.00	229.78	0.00	0.00	3.28	4.79	0.51
	Inconsistently	0.51	2.78	0.74	0.81	2.03	1.08	0.04
	Total	0.49	4.76	0.73	0.79	2.07	1.16	0.36

Table M-1.3
Comparison of random probability for self-consistency with results obtained at different levels in wall context

CONTEXT/ SAMPLE	Percentages and Factors	Consistent (Pure Model State)	Consistent Wave (L+T+C)	Consistent Other Models	N
AIR RANDOM	**%**	1.15	0.03	1.13	15625
AIR COLLEGES	**%**	15.02	7.51	7.51	1132
	Factor with respect to random	13.04	293.31	6.67	
AIR HS	**%**	10.17	4.24	5.93	226
	Factor with respect to random	8.83	165.52	5.27	
AIR MS	**%**	3.16	0.00	3.13	64
	Factor with respect to random	2.71	0.00	2.77	

Table M-1.4
Comparison of random probability for self-consistency with results obtained at different levels in wall context

CONTEXT/ SAMPLE	Percentages and Factors	Consistent (Pure Model State)	Consistent Wave (L+T+C)	Consistent Other Models	N
WALL RANDOM	**%**	1.498	0.03	1.47	15625
WALL COLLEGES	**%**	13.75	6.76	6.99	429
	Factor with respect to random	9.18	211.25	4.77	
WALL HS	**%**	13.25	5.42	7.83	166
	Factor with respect to random	8.85	169.43	5.34	
WALL MS	**%**	7.35	2.94	4.41	68
	Factor with respect to random	4.91	91.91	3.01	

APPENDIX N
RESULTS RELATED TO VALIDITY VERIFICATION THROUGH INTERVIEWS

Appendices N, N-1, N-2 and N-3 deal with findings related to the validation of the test through the interviews. Appendix N presents an overview of these results. Appendix N-1 contains a description of misinterpreted answer choices. Understanding students' misinterpretations was an extremely important result and it was separated so that we can refer to it independently in the dissertation. A detailed table of students' models and answer choices they picked in tests is shown in Appendix N-2. Finally, Appendix N-3 contains transcripts that verify students' mental models shown in the table of Appendix N-2. In the current Appendix (N) we present overall findings starting with issues in determining students' mental models and their mapping on answer choices.

Those students who do not have a model or who are not sure about the correct answer, often like more than one of the answer choices in any of the test questions. When this situation is the case, they may or may not worry about consistency of their answers to different questions. The following statement expressed by a student illustrates these points:

I: When you were taking the test […] do you think you had a ready answer and then you tried to find it in the choices...?

S: No.

I: No. OK. So what did you do?

S: I would flip the choices and then pick which one I thought would be the best answer.

However, the student could have self-consistently picked the choices that correspond to a single model although he or she finds more than one of them attractive:

Below is an example when a student is not sure about the model she initially expressed but decides to be self consistent. The transcript shows the discussion related to question 1 after the student completed the whole test.

I: So in the first question, you picked choice a). So what was what you liked about it and what you didn't like about others?

S: Um, well I chose a) because that's what I talked about to you before.

I: OK.

S: Moves the particles [Silently read a part of the answer she picked to indicate the correspondence of the choice with her previous answers]

I: Uh huh (Yes).

S: And, actually like almost all of these answers I agree with like every single one of them, but I just picked one that I kind of agreed more with. Because they *all* make sense. But they all kind of contradict themselves. But since I really don't know the right answer, I am like "well it could be that too".

I: OK. So you are saying that from your standpoint all of them might be true.

S: Yeah.

I: OK. I see. But did you clearly see how they are different.

S: Yeah, I can see the differences.

The previous example also illustrates that students' reasoning is not static. Conceptual change is a dynamic process and students' understanding may change fast, especially when concepts are not firm and new information is provided (in this case by the protocol). Students are sometimes aware of the change in their reasoning and verbalize it as the following example shows. After reading question 2 that asks about the vibration of the medium particles, a student said:

S: I never really thought about vibrating and how the particles do move, so that this introduces a new idea that I didn't consider for question 1.
I: OK. Can you tell me more? So you are saying that this is kind of prompting you that particles move?
S: Yes.
I: Um, OK. So how would you go about it?
S: Well, I don't know, since it says "vibrate" it kind of gets me thinking of how the sound travels through the particles making them vibrate and [pause] according to my first answer I didn't think they've moved at all.
[…]
S: I think my choice would be between c) and d) and possibly e).
I: OK. So [choice] a) [the choice saying that particles do not vibrate] is not um...
S: No, I thing they do vibrate. And that's what allows the sound to go to the other side.
I: Uh huh (Yes). Now, is this something that this question made you think?
S: Yes, it makes me think of like new possibilities
I: OK.
S: Or new ways of reasoning.

This particular student did have a model (Independent Entity) at the beginning of the interview and questions 2 and 3 made her reconsider not only the particle dynamics but later on (in question Q4) also her whole model. And she was again aware of this change:
I: Do you think that what you [picked], this choice [4e], is the same one that you were earlier explaining sound like?
S: No, it's different.
…
I: You decided to basically change your mind and it required a [un-understandable].
S: Yes.

Details of the interview with this student are presented in Appendix N-3 as case study 3 and in the table of appendix N-2.

For students who initially do not have any model of sound propagation, the interviewer's questions and later on the test choices themselves, provide a rich pool of ideas to choose from, so they pick and sometimes eventually even settle on something that makes the most sense to them. Because of these dynamics, a probing of the validity of students' choices in the test has to be concerned with the time when the answer was given and with the student's "current" ideas or models. A student may express two different opinions at two different times and both of them could be valid. Because of these difficulties, results from the interview protocols will be presented as 17 case studies. Each of them was very unique and only long transcript excerpts can do justice in verifying the researcher's conclusions.

An unexpected result of the interview protocols was that the test answer choices themselves provided material for new hybridizations of models. Specifically, several students hybridized Independent Entity and Dependent Entity Models into a new construction that was not observed in earlier studies. Earlier studies (Hrepic, 2002)identified "independent entity" as a sound unit that, for example, propagates through the vacuum equally fast or even faster than through the medium. In the case of dependent entity, sound was carried by the moving medium particles and their motion either existed all the time (with or without sound) or it was created by the "domino effect" of the particles of the medium, which was caused by the source. In the hybrid that appeared while students were taking the test, the Independent and Dependent Models of sound were recombined in a way that sound entity itself becomes the agent that sets the medium into motion and then this same motion carries it further.

Student 1 fluently described this Dependent-Independent Model as a "package deal" in which "sound causes that motion, but in order for sound to keep moving that motion has to occur."

S: It seems like they work together...type of thing.
I: OK.
S: Like without it [sound] being able to move the air particles it doesn't seem like it would go far.
I: So sound […] moves the air particles and this motion of the air particles... [interrupted]
S: It's a package deal.
I: Can you say it in your own words?
S: Like it seems it has to have an ... almost simultaneously.
I: Alright.
S: Like the sound goes through but the only way that it will actually go through is with that motion of the air particles.
[…]
I: So sound is first?
S: Yeah, and then the air particles.
I: It causes motion and then they take over?
S: Yeah.

The further details of statements expressed by this student can be found in Appendix N, case study 1. Another student, case No. 5, was one of the 6 students (out of 17) that hybridized Entity Models this way. In question 4 she liked both choices b and c. Choice 4b states that the motion of the air particles [that occurs while sound propagates] "is caused by the propagation of the sound through spaces in between the air particles" and choice 4c states that this motion "enables the propagation of the sound through spaces in between the air particles." Because none of the students expressed this Dependent – Independent hybrid on their own in either earlier studies or in this study ***before*** the test, the interviewer asked the student after the test what she thinks is the reason that students, including herself, do not come up with this model on their own but they do during the test. The question for the student was why does she think that this procedure is the case and what happened in her case. She answered:

S: It [the test] breaks it down into smaller pieces that we don't talk about in the interview part. And so this [the test] is asking you to differentiate between one way or the other, and we don't necessarily think of that when telling you [on our own] how it [sound propagation] happened.

This example clearly describes how the test itself may affect the dynamics of the students' reasoning and therefore the answers. A new instrument brings in new issues in interpretation. In the post survey test version, this specific problem was addressed in a way that, where possible, those answers corresponding to the dependent entity are broad enough to include this hybrid too.

Issue of Dependent-Independent Hybrid Model and validity of the choices

After reading the choices related to the dependent and independent entity a number of students felt the need to recombine them into a single model. According to this hybrid (which was regularly created due to the test choices and not by students on their own), sound is created as an independent entity which shakes the air particles. Then once the air particles are set into motion by sound, this motion carries the sound further in a dependent entity mode. In questions 1 and 6, choices corresponding to dependent entity were compatible with this model and the issue was appearing in questions 4 and 5. In the question 4, the problem of this hybrid model has been addressed in a way that the choice that corresponds to the Dependent Model was made compatible with this model too.

The difference between the independent and dependent entity answer options in Q5 is temporal. In the case of independent entity, sound is the shaker of the medium so it moves first (before the medium). In the case of the dependent entity, the medium moves the sound so the motion of the medium occurs first. The source along with the "domino effect" of the movement of the medium particles shakes the medium or the medium moves constantly in the same way. This constant motion of the medium is used by the sound for propagation. To use the analogy that student No. 1 proposed in the case of the independent entity, sound is a horse and particles of the medium are the cart. In the case of the dependent entity, it is the opposite. Some aspects of the answer choices corresponding to the Entity Model in question 5 are compatible with the Dependent-Independent Hybrid Model (which is what makes it their hybrid). But to specifically address this hybrid in question 5, a new answer choice would be needed. Adding a sixth choice was not feasible because of the reasons explained in the introductory part of section 4.5.

Therefore, students who could possibly come up with this hybrid model will be projected into the mixed model state, but only into the mixture that corresponds exclusively to the Dependent and Independent Entity Models. As such they are separated by the analysis program into the section that corresponds to this exclusive mixture within the mixed model state column.

The final word on this issue is theoretical in nature. Four interviewees arrived at this mixture of the Dependent and Independent Model while they were taking the test but it never happened that any of them (in this or earlier studies) arrived at this mixture on their own. This point is crucial in determining the need for and optimal way of addressing this new hybrid. This hybrid concept is a complex but unitary knowledge structure with all attributes of the mental model. However, the test (may) project it as a mixed model state that consists of the Dependent and Independent Models. The question is wether the test is then valid with respect to this particular (single) model if it projects it into a mixed model state that reflect its components.

To answer this question we have to take into account that it never happened that any of the students expressed this understanding on his or her own and after that, while reading the test, he or she could not find the appropriate choice that corresponds to this understanding. If this happened that would clearly demonstrate the invalidity of the test. However, if a student, while reading the test choices, decides to combine (only some) pieces of some of them into a new answer he or she will have difficulty about which of the existing ones to pick. He or she has two options:

1) To settle on one of the models as offered in the test (one that for whatever reason seems more plausible) and then to consistently use that model throughout the test, or
2) To pick choices corresponding to any of the two "parental" models in different test questions.

In the first case a student would make his or her choice and be projected into a pure model state that corresponds to the model of his or her choice. The result, as projected by the analysis, in this case is therefore valid. In the second case, the test projects the student into a mixed model state – and if a student could not settle on one of the models, then the mixed model state is *exactly* the state in which he or she is in.

Results of the interview validation

Detailed results of the interview are presented in the appendices N, N-1 and N-3 in an essay format and in tabular format in Appendix N-2. The overview of results for all 17 interviewed students is presented in the Table N.1.

Table N.1
Results of the test validation through the interview

Student No.	**No choice as desired**	**The answer that the student chose was not the closest match to the expressed model because of the:**			**Test choices consistent with stated models?**
		Misread statements	**Statements read into**	**Misinterpreted statement**	
1.					Yes, All
2.			5e	5a	Yes, All
3.					Yes, All
4.					Yes, All
5.	In Q5				No, not Q5
6.					Yes, all
7.	In Q6		4b		Yes, all
8.					Yes, all
9.		4d			No, not Q4
10.		1d		5a	No, not Q1
11.					Yes, all
12.		1e			Yes, all
13.				6a	No, Not Q6
14.					Yes, all
15.				5a	Yes, all
16.				5a	No, not Q5
17.	In Q5			5a	No, not Q5

In Table 4.9 we differentiate and report on answer items that were identified as "misread," "read into" and "misinterpreted." Differences between these instances are explained below. It also shows instances when a choice desired by a student was not offered among the answers are reported. The final column states whether models that correspond to choices that were picked in the test correspond to the models that were expressed verbally. If a student's answer is not valid, the question in which the probe was invalid is indicated.

Issues defined

Misread statements are defined as instances in which a student misinterpreted the statement because he or she overlooked something in the text. When the statement was misread and an omission later noticed, students' reactions were of the kind: "Oh, I didn't' notice … ." When the problem was noted, students would quickly abandon the invalid choice and choose one that is aligned with the model they described orally.

This easy change was not the feature of the cases with "statements read into" and misinterpreted statements." By "reading into" the statement, we mean instances when students gave an extra meaning to the statements, which is not objectively written or when some parts of the written text were ignored. Unlike the cases of misread instances, when statements "read into" were pinpointed to students during or after the interview, they usually had difficulty seeing the researchers' viewpoint and were hesitant to agree.

Misinterpreted items were understood in a way not intended by the test writers but not because a student "added" something extra to them but rather because some crucial parts of the text were not understood properly. The main difference between statements "read into" and the "misinterpreted" ones is that the later ones are "fixable." Better wording of the choice can solve the problem in these cases. However, in order to address the "read into" statements, one would have to write everything that the choice does not mean, which is not feasible and as long as these are rare instances, they can be ignored.

From the perspective of the test developers misread things can not be controlled which is why misinterpreted items are much more important findings (as long as misread items are not frequent). However, not all instances of a misinterpreted item caused the probe as a whole to become invalid. Sometimes they were not needed (did not correspond to the expressed model and sometimes the secondary model choice was picked instead of the primary one). If the choices that a student picked were nevertheless consistent with the models that he or she expressed, then the misinterpreted item did not affect the validity of the probe although it did affect the validity of the test. For this reason, Table 4.9 displays not only misinterpreted answers but also has a separate column that shows whether the probe was affected. In addition to the tabular representation of the findings each case noted in Table 4.9 will be separately addressed with important highlights.

Occurrences of "no desired choices"

Two of the three instances where a desired choice was not found were related to question 5 and in both of these cases simultaneous timing of the particle dynamics and the sound propagation was needed. Only one choice offered this simultaneous timing but it was as a part of the answer corresponding to the Intrinsic/Wave Model. Although neither of these two students liked the second part, they nevertheless picked the choice with simultaneous events. This simultaneous part was what they needed and they decided that the answer best fit their choice regardless of the rest of it that they did not agree with. These two students are numbers 5 and 17. Student 5 needed simultaneous timing because in question 4 she developed the Dependent-Independent Model. Student 17 had more complex reasons that are described in Appendix N-3 (Case 17).

A third instance when a choice different from those offered was needed was related to question 6. This student had the Dependent Entity Model and choice 6a) best fit with it, however, she was annoyed with the phrasing "sound can exist in the vacuum…" in that choice. She knew for a fact that "it can't." When she took the test the first time, she picked the dependent entity choice in question 6 as well as in all other questions. But, later on in the second reading she decided that choice a) was not close enough to what she wanted so she picked another one thus causing that the answer in question 6 to no longer be aligned with her expressed model.

Occurrences of "misread statements"

Unlike previously mentioned instances when a second reading caused a shift away from the expressed model, there were two instances when a second reading created valid self consistency. Both of these instances were according to the above definition classified as the misread items. Students 9 and 10 overlooked the term "air particles" and interpreted it as "sound particles" in choices 4d and 1d (of the wall context) respectively. Both of these students realized their "mistake" in the second reading and picked the choices that were aligned with the models they verbally expressed. However, these probes were classified as "invalid" because in all instances we analyzed results of the test as they were given in the first reading.

One specific case of a misread statement was on the borderline of the categories we devised. Namely, student 12 read into choice 1e, but once she was asked about it (not on her own) she easily dismissed the original choice and chose one that corresponded to her model. Choice 1e was a secondary choice for her model and did not cause invalidity of the probe. The details of this situation can be found in Appendix N-3, case 12. Because of the ease with which this student made the shift, this occurrence better fit the category of misread choices than "read into" choices and was classified accordingly.

In instances when students changed their answer choices in the test for whatever reason, the validity of the probe was determined based on their first choice. The rationale was that without the interview this first choice is what would have appeared as a test result. In four of these instances (already described above) and in two cases the new selection was aligned with the expressed model (and thus it created the validity of the probe) and in one of them the new choice broke the validity of the probe. In one case there was no difference as both choices would have been validly interpreted. Instances in which the choice was changed are indicated in the table in Appendix N-2 with arrows so the final answer is placed on the right side of the arrow.

Occurrences of "statements read into"

In two instances students attributed the meaning to the answers that reached beyond the written text or that ignored some parts of the text. Student 2 misinterpreted the answer 5e) which goes as follows:

5. The motion (or lack of motion) of the air particles that you described in previous questions

e) … exists all the time the same way, with or without the sound propagation.

This student interpreted this choice as if it was saying that air particles exist with or without sound. She basically ignored the first portion of the sentence which says "*the motion* of the air particles…" (not the air particles themselves).

Student 7 read into answer 4b. The question and choice are:

4. Complete the following sentence: The motion (or lack of motion) of the wall particles that you described in previous questions…

b) …is caused by the propagation of the sound through spaces in between the wall particles.

This student superimposed a meaning to this saying that, according to the statement, without sound the wall particles do not move at all. This is a kind of reading into the statement (or assigning meaning to it) that is not addressable.

Misread and read into statements have in common that they could not be solved. The only thing that was done in order to decrease the chance of overseeing "air particles" in the wall context (where wall particles and sound particles are also mentioned) was to flip the order of words and in cases when air particles are what we dealt with we wrote "particles of air." Due to this difference in the phrase structure, it is more likely that the choices will be understood properly.

Occurrences of "misinterpreted choices"

Because of the importance of misinterpreted choices they are described on their own and in the next appendix (N-1) so they could be referred to separately in the text.

APPENDIX N-1
MISINTERPRETED CHOICES
(A continuation of Appendix N)

In the case of misinterpreted choices there was no factual ground for misinterpretation; however, the problem in these cases was fixable.

A misunderstanding related to choice 5a was frequent. In all of the six instances when the problem occurred, the choice was misunderstood in the same way. This is question five and choice 5a:

5. Complete the following sentence: The motion (or lack of motion) of the air particles that you described in previous questions…

a) …occurs before the sound can propagate through spaces in between the air particles, as a precondition for propagation.

The word "before" here refers to "propagate" but six different students understood this statement as if it claimed that the motion of the air particles occurs before the source creates the sound. Some of these students had a Dependent Entity Model (that choice 5a primarily corresponds to), but they found this choice implausible because the sound "can not be anticipated." This problem was solved in later versions of the test.

Besides those misinterpretations with respect to choice 5a, there was one misinterpretation related to choice 6a) that was made by student 13. This student had a Wave Model before the test and used it consistently until Q6 where she picked choice 6a) (dependent entity).

Question 6 is: "Can sound propagate through a vacuum (empty space without matter)?" And choice 6a says:

a) No. Sound can exist in empty space without particles of matter, but it needs the motion of those particles to be carried to another place. (A vacuum has no matter so this is not possible).

What makes this choice incorrect is the statement that "Sound can exist in empty space," because in empty space there is no sound. However, this student picked this answer as a correct one and gave the explanation that there has to be a source of sound placed in this vacuum because the question asks whether or not the sound would propagate. If a source exists within the vacuum (and the question implies it does), then sound exists *within* that vibrating source. And, because there is an empty space around the source the sound can not propagate.

Although this reasoning does not make the mentioned part of the statement correct (we speak about the propagation through the *empty* space there), the explanation that this student gave is both thoughtful and meaningful so we decided to reconsider the question in order to reduce the possibility of a similar reading into the answer in the future. Namely, it is true that neither the question nor the answer were mentioning the source, however, it is also true that they implied one. And if one reads "Sound can exist in empty space" while keeping in mind a source is in that empty space, then the answer of this student is correct in a way. The problem with that answer is that if sound within the source is considered, we do not talk anymore about the empty space. This misinterpretation was unique, but we reconsidered question 6 and added a picture to it with the source floating in the empty space.

APPENDIX N-2
TABULAR REPRESENTATION OF THE MODEL DYNAMICS DURING THE INTERVIEWS

Table N-2.1. Students' model dynamics during the validation interviews

#	Results: Models expressed					Input effect	Probe validity
Student (case) No.	In the discussion before the test	In the discussion during the test	In the test choices	In the discussion after the test AND in changed test choices	In graphics	Model dynamics affected by protocol?	Test choices consistent with models
1.	N/A	1: Intrinsic 2:Independent 3: Dep/Ind combination	1: Intrinsic 2:Independent 3: Dependent (b,b,c,b,c,a)	1: Dep/Ind combination (a,b,c,b,c,a)	1: Dep/Ind combination	By test	Yes, All
2.	N/A	1: No model 2: Dependent	1: Dependent (c,c,e,c,e,a)	N/A	1: Dependent (Choice 3)	By test	Yes, All
3.	Independent	1: Independent 2: Wave	1: Independent Q1: (e) 2: Wave Q2-6:(ccedb)	N/A	N/A	Refined by interview Affected by test	Yes, All
4.	1: No model 2:Independent and Dependent	1: Independent and Dependent 2: Dep/Ind combination	1: Independent and Dependent (a,e,c,b,c,a)	N/A	N/A	By interview & by test	Yes, All
5.	1: No model 2:Dependent	1: Dependent 2: Dep/Ind combination	1: Dependent 2: Dep/Ind combination 3: Intrinsic (e,e,d,bc,d,a)	N/A	N/A	By interview & by test	No, not Q5
6.	1: Wave / Intrinsic (Dynamics not defined)	N/A	Wave (b,e,b,e,d,b)	N/A	Wave (Choice 1)	By test	Yes, all
7.	1: Dependent and Independent	N/A	1: Independent 2: Dependent 3: Intrinsic (e,b,d,c,a,a→b)	N/A	N/A	No evidence of change	Yes, all

#	Results: Models expressed					Input effect	Probe validity
8.	1: Dependent 2: Wave (at the very end and with the post test statement)	N/A	1: Wave (b,c,b,e,d,b)	1: Wave	1: Wave Dependent recognized as the initial answer	By interview	Yes, all
9.	1:Independent	N/A	1:Independent (a,e,d,d→b,c,d)	N/A	1:Independent	No evidence of change	No, not Q4
10.	1: No model 2:Independent and Dependent and Ear-born	N/A	1: Dependent 2: Dep/Ind combination 3: Ear-born (d→c,c,c,c,c,c)	N/A	1: Dependent (Choice 3) + Ear-born	By interview	No, not Q1
11.	No model Independent and Dependent ideas without commitment	1: No model 2: Dep/Ind combination	1: Intrinsic 2: Dep/Ind combination 3: Dependent (b,b,d,b,a,a)	N/A	Recognizes as his choices: 1: Intrinsic 2: Dependent (Choices 1 and 3)	By interview, By test	Yes, all
12.	Wave	N/A	Phonon – Wave (e→b,d,b,e,d,b)	Wave (b,d,b,e,d,b)	Wave (Choice 1)	No evidence of change	Yes, all
13.	Wave	N/A	Wave (b,c,b,e,d,a)	N/A	Wave (Choice 1)	No evidence of change	No, Not Q6
14.	No model	N/A	Independent &Ear-born &Intrinsic (a,b,d,d,b,b)	N/A	Intrinsic (Choice 2) & Ear-born	No evidence of a model	Yes, all
15.	1: Dependent &Independent	N/A	1: Dependent &Independent (a,d,b,b,c,a)	N/A	Independent in wall (Choice 4) and Dependent in air/vacuum (Choice 3)	No evidence of change	Yes, all
16.	N/A	1: Dependent	1: Dependent &Independent (c,c,e,c,e,a)	N/A	1: Dependent (Choice 3)	No evidence of change	No, not Q5
17.	N/A	1: Dependent	1: Dependent &Intrinsic (e,c,c,c,d,a)	N/A	1: Dependent (Choice 3)	No evidence of change	No, not Q5

APPENDIX N-3
ANALYSIS OF INDIVIDUAL INTERVIEWS – CASE STUDIES

This appendix has two purposes. The first one is to provide details related to specific cases mentioned in the text of the dissertation (and in Appendix N) through longer transcripts. Cases that were mentioned earlier will be elaborated in greater detail than others. Another purpose of the appendix is to verify conclusions related to their models that are shown in the tables of Appendix N-2.

CASE STUDY No. 1

Student No. 1 is a good example of the simultaneous selective mixed model state (likes more than one specific model at the same time). He also provided an elaborate account of a model of sound propagation that appeared in several instances due to the test taking that we labeled Dependent-Independent Hybrid Model. For these two reasons the interview with student No. 1 will be presented with additional attention.

Overall this student understood the choices, but in all relationship defining questions (Q1, Q4, Q5, Q6) he could not decide which of them was correct. In different instances and because of the different reasons he picked answers corresponding to any one of the three models he was considering. He picked an intrinsic choice in question 1 although three particular choices were attractive to him. Questions 2 and 3 prompted him to rethink the role of the particle dynamics and in question 4 he picked an option related to the Independent Entity Model. In Q5 he decided to be consistent with his answer to Q4. In Q6, because he knew sound does not propagate through the vacuum, he eliminated Independent Entity and switched to the Dependent Entity Model. In all of the relationship defining questions (Q1, Q4, Q5, Q6) he expressed a certain degree of interest in all three of the models.

In a discussion after the interview the student settled on a Dependent-Independent Hybrid Model. The student was using a horse and cart as an analogy of the mover and the moved. In the case of the Independent Model, sound is a horse (mover) and the air particles are the cart (moved). In the case of the Dependent Model it is the opposite. While taking the test, when the student picked the independent entity choice in two of the questions, he compared sound to a horse (mover) in accordance with the mentioned analogy. In question 6, however, the student picked the choice corresponding to the Dependent Entity Model so the interviewer brought up the student's earlier statements antd analogies made to justify the Independent Entity Model. At this point the student developed and eloquently described a generic Entity Model. So, this case nicely shows the mixed model state as well as hybridization of the dependent and independent idea. Below are transcripts with shorter comments.

This is how student 1 interpreted the difference between choices 1a and 1c, related to the Independent and Dependent Entity Models:

QUESTION 1:

I: Can you see what would be the difference between c) and a)?

S1: Um...I would say that 1a) like...have you ever heard the cart before the horse analogy? Like put the cart before the horse?
I: Uh huh (Yes). Yeah, I can see what it means.
S: Yeah. It seems like 1a) you have the sound moving and...like the sound is moving through the empty spaces and is causing the air particles to move. It seems logical to go in that order. 1c) just...to me anyway, doesn't seem logical for air particles to be moving and then sound going through them because the air particles are moving.
I: So basically the difference is that in one case you have horse and then cart and in another case you have cart and then horse?
S: Yeah. Yeah.

The student also fully understood the choice 1b) that he also found attractive:
S: [Reading 1b) silently] Like this just says to me that sound IS, like sound IS the motion of the air particles.
I: So is it clear?
S: Yeah. I mean, it's pretty cut and dry.
I: OK. Now you may decide what seems the most plausible.

The student found more than one answer choice "really attractive." He chose one of them based on three factors: (1) Simplicity of the answer 2b) and (2) implausibility of the order of events in the case of dependent entity (motion of particles before the sound) and (3) slight implausibility of the idea that sound passes "in-between the air particles."
S: In [the question] number one, 1a) through 1c) are the really attractive answers to me.
I: OK.
S: And d) and e) just, just don't seem like they would answer the question. Um, we talked about a) and c) a lot. I think b) is a pretty attractive answer because it's simple. And it seems like a lot of people think about...there should be a complicated answer but it might be simple.
I: Alright.
S: I kind of would just go with that [the answer b)].
S: OK. Great.
S: And it makes sense too. The sound is the motion of air particles.
I: OK.
S: So...
I: Would you go with the b)?
S: Yeah, either a) or b). [Not understandable] when I took it in class. Pause. Um...Yeah, I'd probably go with b) now.
I: OK. What is it in number [choice] a) that makes it also attractive? Because...
S: It just...like whenever I'm analyzing it, um, it seems like it follows the correct order of what I've been taught. Like sound is moving through air and is causing air particles to move.
I: OK. OK.
S: And b) sounds, sounds good because, I mean "sound IS the motion of air particles".
I: You said earlier that this concept of sound propagating through the empty spaces in between the air particles is not something that you would...

S: Are you talking about c)?
I: Umm, right c), I think it was c). In number a) you have the same concept as in c) {same wording "through the empty spaces in between the air particles"]?
S: a) is kind of the same as c) but c) seems to be putting that analogy that we talked about, the cart before the horse, in the wrong order.
I: In addition to this concept that you mentioned earlier that is difficult to you to imagine. You remember when you said that something going in-between the air particles...
S: Uh huh (Yes).
I: Do you think number [choice] a) has that problem?
S: Yeah. It still does have the same problem. I don't see anything going in-between the air particles but...
I: But the order seems to be right?
S: But it makes more sense than c), I guess.
I: OK. So let's pick at this point one [of them].
S: I would choose b).
I: OK. Great. So let's move further.

So, the student liked the choice related to the Independent Entity Model ("...sound is moving through the empty spaces and is causing the air particles to move. It seems logical to go in that order."). And the problem with the dependent choice was that things in that case happen in the "wrong order" (" [choice] a) is kind of the same as c) but c) seems to be putting that analogy that we talked about, the cart before the horse, in the wrong order."). After discussing the dynamics of the air particles with the interviewer for 10-15 minutes, the student found choices in question 4 corresponding to the Independent, Dependent and Intrinsic Model all attractive. However, he changed the preference and this time picked the choice corresponding to the Independent Model. Now he found the idea that motion of the sound particles is intrinsically the sound - implausible.
QUESTION 4:
The student reads question 4, makes a long pause and then picks the Independent Entity Model.
S: So b), c) or e). [Pause] I would say "is caused by the propagation of the sound".
I: Uh huh (Yes).
S: Because I think in my answers in previous it seemed like whenever the sound hit it that's when the air particles were moving. And it wouldn't necessarily enable the propagation of sound. Because that's the cart and the horse analogy. And I don't think it is the sound. Because we talked a lot about air particles moving and it just doesn't make sense to me. I wouldn't see that as an answer. So...
I: OK.
S: I think it would be b).
I: OK. Great. Just to make sure for the record. So by answering, choosing b) you decided that what goes first, what goes second? Can you just say it...
S: Yeah, it seems like the sound occurs, the sound propagation occurs and then it causes the motion of the air particles.
I: OK.

So this time the Independent Entity idea prevailed and the choice was made accordingly. Sound is a "horse" and air movement is "a cart." I stress this here because when the vacuum context is presented to the student in question 6, this idea will hybridize with the previous knowledge that sound does not propagate in the vacuum, which will result in the development of a rich Dependent-Independent Hybrid Model. Here in question 4 the student still "stayed away" from the dependent entity which can be seen from his statement that: "whenever the sound hit it [the air particles], that's when the air particles were moving. And, it wouldn't necessarily enable the propagation of sound."

QUESTION 5:

In question 5, the student eliminates the dependent entity choice [5a] because he is after the Independent Entity Model.

S: [Reads 5a)] That one wouldn't be right. Because I said that sound actually makes the air move so it can't occur before the sound can propagate.

S: [Reads 5b)]. No, that's not right. That's the same as the eardrum thing in the question number 1.

S: [Reads 5c)] That makes sense.

S: [Reads 5d)] Makes longer pause.

S: And e) [Reads 5e)] I don't think that's right because I said the air particles move when sound hits them.

I: Alright.

S: So that wouldn't make sense.

I: OK.

S: Um… c) and d) again. [Reads 5d)] [Pause]. I would say c) because of what I kind of like, what I answered before about the sound hitting the air particles and then the air particles moving.

I: Alright.

S: And d) just seems like [pause] um...the sound is the air particles moving [said in the tone that says "which is not plausible"].

I: O.K.

S: Does that make sense?

I: Yes it does.

The student's choice in Q5 is consistent with his previous answer given in Q4 (independent entity) although he again contemplates the intrinsic idea.

QUESTION 6:

In this question the student decided that the answer is "no" before even reading the answer choices because of the experiment he saw in the classroom.

S: And [question] 6. [Reading the question] No. [Pause] She [the instructor] did an experiment about this. Sound didn't go anywhere. So...I would say no based on that.

[Reads 6a)] That makes sense 'cause you can't carry the sound when there's no air particles moving. [Pause] Sound does exist but it needs the air particles...yeah. That makes sense.

[Reads 6b] What we are talking about here and the number 5d) is kind of the same thing.

I: You mean 6b) and 5d)?

S: Yeah.

I: Yeah.
S: It seems like air particles moving is sound [un-understandable].
I: Yeah. That's the match.
S: So based on my previous answers, I don't think that's right.
[Reads 6c] No.
[Reads 6d] I would say no. Not at all. Just based on the experiment that she [the instructor] did.
I: What was the experiment?
S: Um. She [the instructor] had a bell and she put in a vacuum in it. We couldn't hear it.
I: So based on that experiment you eliminated d).
S: Yeah. And also...I don't know, it seems like sound kind of needed air particles even if it was just going in-between them and spread them out.
I: Can you repeat that please?
S: Like it seemed like sound...in order for sound to move it had to have the air particles to move in between, or to move through because we concentrated so much on air particles moving and everything that...you know, why would sound be able to exist without that movement. [Pause] I guess. So I'm guessing it might be the answer.
I: So what would you say in [question] number 6? So what do you think about [choice] e).
S: [Reads 6e] That just...that makes sense. Like there is nothing to obstruct, then it would just go through. You can't resist the sound propagation at all. You can't bring it down. So yeah, it makes sense.
I: So what would you go with?
S: I would go with a) but now that I am starting to think a little bit (pause)
I: Uh huh (Yes).
S: b) sounding attractive too... And that would mean that a lot of my answers to previous [questions] would change, but (pause)...
I: And that would what?
S: Like b) kind of sounds like it could be about an answer also, because like with the vacuum experiment there are no air particles moving and it seems like air particles moving in that instance could possibly be sound.
I: Uh huh (Yes).
S: Or it might just be carrying the sound. So I don't know. That's all [unintelligible] would be. I would say a).
I: So from this experiment you concluded it's either a) or b)?
S: Yeah.
I: c) also says "no" and it says [reads 6c)].
S: Sound exists. I think sound exists before it hits somebody's eardrum.

So, the student's recall of the experiment with a bell in a vacuum caused a shift to the Dependent Entity Model at this point. The transcript below shows that the intrinsic choice (6b) and independent choices (6d, 6e) nevertheless sounded attractive to the student. The transcript below also shows that the interviewers follow up with a question that caused development of the Dependent-Independent Hybrid Model.
I: Let me tell you the only thing that from my perspective seems to be inconsistent.

S: OK.
I: In [question] number 6, if sound is a horse, why it wouldn't… So you just know from the experiment that it doesn't move through the vacuum but if it's a horse then it should really, right?
S: You know... Yeah, kind of. You know, why... Um, it seems like they work together...type of thing.
I: OK.
S: Like without it [sound] being able to move the air particles it doesn't seem like it would go far.
I: So sound is horse, it moves the air particles and this motion of the air particles... [interrupted]
S: It's a package deal.
I: Can you say it in your own words?
S: Like it seems it has to have an... Almost simultaneously.
I: Alright.
S: Like the sound goes through but the only way that it will actually go through is with that motion of the air particles.
[Change of the tape side]
I: Alright. So you were saying that it's almost simultaneous.
S: Yeah. Like it seems like sound causes that motion but in order for sound to keep moving that motion has to occur.
I: So it's the package deal.
S: Yeah. It's the package deal.

During verification of the model through the graphics, the student picked the Dependent Entity Model in accordance with the idea of dependent entity with the "package deal amendment" to it:
S: Sound helps... The air particles help sound and they both work together like we talked about the package deal thing.
I: Right, right. So sound is first?
S: Yeah, and then the air particles.
I: It causes motion and then they take over?
S: Yeah.
I: Alright.

CASE STUDY No. 2

Student No.2 at the very beginning did not know how to answer the question about propagation. So she started with no model. Then after some of the discussion about sound and the air (according to the interview protocol) the student expressed an idea that is vaguely aligned with Dependent Entity Model.
I: Can you put sound and air into perspective. You know, how they treat each other?
S: I would say that air can help the sound travel.
I: Alright.

S: But I don't know about motion of air or anything. I don't know how that would change.

In order to clarify that statement, through follow up question the interviewer elicited an understanding that corresponds to Dependent Entity Model. Transcript below shows this:

I: OK. How it helps it travel?
S: I would have to completely make that up. I don't know.
I: OK. OK. So the idea is that we have air…
S: Uh huh (Yes).
I: then somebody creates sound
S: Uh huh (Yes).
I: And then air helps sound travel.
S: Uh huh (Yes).
I: And sound and air are two different things
S: Uh huh (Yes).
I: OK.

After this, the student consistently picked choices related to the Dependent Entity Model in all of the questions except in Q5 where she did not recognize choice 5a) as pertaining to her ideas. She shifted to answer 5e) which she picked reluctantly. Choice 5e) also pertains to the dependent entity, i.e. to the sub model according to which air particles vibrate all the time in the same way.

In question 6, the student eliminated answers d) and e) because she knew for a fact that sound does not propagate through the vacuum and picked choice a) and that way confirmed the model as dependent so her choices were aligned with a model all the way through.

CASE STUDY No. 3

Student No. 3 changed her model while taking the test based on inputs that she found in the test questions and answer choices. She was aware of this change. The student first expressed the Independent Model in the interview before seeing the test questions.

I: How sound propagates through the wall?
S: I think they travel like in the space provided through the molecules and like just travel through them.
I: OK. What would travel through them?
S: Sound.
I: Sound. Could you describe this sound to me?

As an answer to the above question, the student stated that sound propagates as a wave but she could not give any explanation or definition of what the wave was. The interviewer proceeded with:

I: Do wall particles play any role in this process of sound propagation or not.
S: I think so.

I: What. What would be their role?
S: Um, I think they trap some at the same time and they also provide the barrier so it traps some of the sound. That's why you can't hear clearly on the other side of the wall.
I: OK. So one kind of obstacle for sound.
S: Yeah.

The student had a different idea related to the role of the air in sound propagation:
I: Does air play any role, or air particles? Because we have air on both of these sides?
S: Yes, it does.
I: Is that the same role as the wall has or...
S: No, I think the air helps the sound waves.
I: It helps the sound waves.
S: Uh huh.
I: OK.
S: When it goes through the wall particles, then [wall particles] are an obstacle.
I: Can you tell me a little bit more about that?
S: Of the...
I: How are they different so that, I mean how are the air particles and the wall particles different so that air helps and wall obstructs?
S: Well with air, the wall particles are like solid whereas air is more gas.
I: OK.
S: And that's what the makes the wall an obstacle because they're obstacles and sound is in trouble [not understandable] through solid.

When asked about the relationship of the sound and the air, the student answered:
S: I think that the air allows the sound to pass through it.
I: OK.
S: And [pause]
I: Does it play a role of helper in the process or it's just not an obstacle?
S: I think it helps the sound wave [to] travel through the medium.
I: OK. So are they, the air particles and sound, are they two different things, or the same thing...?
S: The sound wave travels through the air. The air is the medium provided.
I: Yeah. But when you said earlier the sound goes in-between the wall particles, does the same thing happen in the air or its something...
S: I guess it's the same but the...being there the more condense, it's harder for the sound wave to travel straight through, whereas the air is more...its less dense than a solid wall.
I: OK. But in principle sound goes in-between the air particles?
S: I think so.
I: So in a same way as it does through the wall, but the air is less dense.
S: Uh huh (Yes).
I: Therefore, it's less of an obstacle?
S: Uh huh (Yes).

I: And it also helps, did you say, it also helps sound? It's not just that it's less of an obstacle, does it also kind of...
S: I think so.
I: It also helps sound unlike wall.
S: Uh huh (Yes).

The above transcript shows that the student's model related to the wall context was the Independent Entity Model while her model related to propagation through the air had elements of the Dependent Entity Model. The test that the student took was the wall context test. In the test she picked the independent entity choice according to her model associated with sound propagation through the wall. In question 1 she also decided that the wall particles do not move due to the sound propagation. Later on, because of the very fact that questions 2 and 3 ask about this movement, the student changed her mind and decided that they do move due to the sound propagation. While answering question 2 she also began considering the idea that the sound is a dependent entity from question 1. Transcripts below are included as a verification of these conclusions. After reading question 1 and its choices the interviewer asked:
I: So how would you answer this question [1] and why? Which of these choices, if any, seem to be plausible?
S: I think I would answer e) because [pause] in most of the other answers it's saying that sound affects the particles that make up the wall.
I: Uh huh (Yes).
S: And I don't really think that the particles in the wall, since it's the solid are moving around too much.
I: Right.
S: So I think it's the sound [short pause] particles that move through it, and not the wall particles or the air particles.
I: Yeah, one of the answers had the air particles going... Yeah. When you say too much, what do you really mean?
S: I know that the wall particles...everything that it's made of… has slight movement...
I: Right.
S: But since it's the solid they're pretty dense and they don't move around really.
I: Does sound affect this motion or not?
S: I don't think it does.
I: OK. Great.
So you picked choice e) because other [choices] refer to this movement?
S: Uh huh (Yes).
I: OK. Great. Can you go further please?

QUESTION 2

After reading question 2 the student said:
S: I never really thought about vibrating and how the particles do move, so that this introduces a new idea that I didn't consider for question 1.
I: OK. Can you tell me more? So you are saying that this is kind of prompting you that particles move?
S: Yes.

I: Um, OK. So how would you go about it?
S: Well, I don't know, since it says "vibrate" it kind of gets me thinking of how the sound travels through the particles making them vibrate and [pause] according to my first answer I didn't think they've moved at all.
I: OK. So is there any choice there [in the Q2] that would correspond to that?
S: For question 2?
I: Yeah
S: I wouldn't say that they vibrate randomly.
I: Uh huh (Yes).
S: And I think my choice would be between c) and d) and possibly e).
I: OK. So a) is not um...

The student was perfectly aware of the change in her reasoning:
S: No, I think they [wall particles] do vibrate. And that's what allows the sound to go to the other side.
I: Uh huh (Yes). Now, is this something that this question made you think?
S: Yes, it makes me think of like new possibilities
I: OK.
S: Or new ways of reasoning.

And the new way of reasoning was the Dependent Entity Model:
I: OK. OK. Now you decided that, as you said, they possibly move and this movement, what's the role of this movement?
S: Huh?
I: I mean, this movement, what it has to do with the sound? This movement of air or of wall particles?
S: I think it has to do with like the transmission of sound from one side to the other. Since it's a wave.
I: OK. So the movement of wall particles will...[pause] can you please just...I think I know what you mean, but I would like you to say it.
S: I think they vibrate and I think they would move back and forth.
I: OK. And how would this relate to sound?
S: I think that's what would reflect the sound to pass through?
I: "Reflect" meaning...?
S: It would carry the sound.
I: OK. I just wanted you to say it.
S: It would carry the sound.

After picking longitudinal vibration combined with the traveling away from the source (in Q2 and Q3), the student in question 4 decided she likes the best the answer that says that that motion is the sound. She was again aware of the change in her reasoning and clearly understood and validly interpreted the answer choices. In questions 5 and 6 she consistently applied this intrinsic idea. Question 4 is where a major change in model occurred.
QUESTION 4:
S: Number 4. [Reads the question and choices.]

S: Pause
I: Do you think you understand the question?
S: Uh huh (Yes) [Pause].
I: You are just trying to figure out what choice would make sense?
S: Uh huh (Yes). Yes.
I: OK. Can you think aloud through it? Like...
S: I am wondering if sound...like e) is, the answer would be "is the sound". I'm wondering if that...That's kind of confusing. Because I'm wondering if what these really are ...they're all, they're all, they're all by definition sound. I am confused.
I: Could you please repeat the last sentence.
S: I am confused because e) is, the answer would be "is the sound"
I: Right
S: [Reads] The motion of the wall particles that you described in the previous questions is the sound.
I: OK.
S: And [Pause] I think that that would be my answer.
I: OK. So, how about others?

At this point the student demonstrated she understands the choices but she did not like the Independent and Dependent Entity Models anymore.

She did not like choice a) that reflects the constant motion of the wall particles because she decided earlier that sound does affect the motion of the wall particles.
Choice b) that reflects Independent Model was eliminated because she believes sound may propagate not only between the wall particles but also throughout them.
Choice c) that reflects the Dependent Model was eliminated because the motion of the wall particles may facilitate the sound propagation but might not be necessary for sound propagation.
Choice d) that speaks about air particles going through the wall was also not plausible. No reason was given.
S: OK. So I am trying to form[ulate] the answer. [Pause] The motion of the wall particles that I described is the motion of sound. And that's how I'm thinking. That's...
I: OK. Could you please explain me that.
S: Because I just answered questions that the motion vibrates and the motion travels and to me I'm describing the motion of the sound. Like the sound wave.
I: OK.
S: So, so the motion that I just described is the motion of sound. That's why I would pick e).
I: So you are saying that...choice e) says that that motion is sound.
S: Uh huh (Yes).
I: So that's what you are saying is what you picked?
S: Yes.
I: Now, can you try to put these things together for me. Because I appreciate the last thing you told me how you developed, the whole thing.
S: Uh huh (Yes).

I: Now, do you think that what you, this choice [4e] is the same one that you were earlier explaining sound like?
S: No, it's different.
I: It's different. OK. That's great. Could you tell me did you kind of deliberately decide this one is better for some reason or... Because earlier you were saying that you know, it helps it propagate and things.
S: Uh huh (Yes).
I: Which is not that really [the choice] e) is. Now when you say it IS sound, is it just that this choice seemed plausible?
S: Yes
I: That you decided to basically change your mind and it required a [un-understandable].
S: Yes.

After this the student explained that it was questions Q2 and Q3, which talk in detail about the motion of the wall particles that made her think that 4e) may reflect the actual relationship of this motion and the sound. In questions Q5 and Q6 the student picked choices that correspond to her decision in question 4 which is the Intrinsic Model. At the end of the interview part the interviewer recapitulated and the student confirmed that she changed the model from Independent entity to Intrinsic Model. In question Q1 the student was consistent with her initial verbally stated model. Question 2 prompted her to consider Independent intrusive and dependent entity options. Finally Q3 together with choices in Q4 causes her to decide that the Intrinsic Model is the correct one.

CASE STUDY No. 4

In this case, the student started without any idea about the sound propagation and during further discussions developed ideas consistent with the Independent and Dependent Models. The student's answers in the test reflected both of these models in accordance with her initial statements and also in accordance with the Dependent-Independent Hybrid Model that she developed during the test. The segment below initially shows no model state.

S: When the speaker speaks the sound of her voice gets through wall, vibrates through the wall and comes out as a murmur maybe or as some sort of sound.
I: When you say vibrates through the wall, what do you exactly mean by that?
S: I have no clue but that sounded good.
S&I: Laugh
S: I don't know. I would just, somehow it gets through there. I don't know whether...I've never thought about it. Quite honestly. How it gets through. I just know it happens. Cause I've had that experience when I've heard sounds on the other side of the wall but I don't know what they're saying.

During the pre-test interview she first expressed ideas that pertained to the Independent Entity Model:

S: Well, maybe the wall absorbs the sound that's coming from the speaker and it goes through the wall and it comes out as a... I mean kind of the wall might be like an insulator. That's why it's [sound] maybe is strong at the side where she's talking and then it gets less and less and less [until] it gets on the other side.

During further discussion, the student added dependent entity ideas. After the student mentioned that "sound waves get absorbed" the interviewer asked her to explain what a sound wave is. The student responded in a way that indicates the entity notion of sound.

S: I don't know. Just what is coming out of her. The noise that she's making when she's talking.
I: OK. What would be the role of the wall and the air in this propagation?
S: I guess the air would carry the sound and the wall would absorb the sound that's carried and pass it on. Just pass it on through it.

Previous transcripts show the Independent Entity Model and Dependent Entity Model. The student's answers in the test reflected both of these models. While answering question 1, the student disregarded answer 1b related to intrinsic / wave motion because:

S: The second one sounds scientific but the first one sounds like it would be more appropriate.
I: Because of?
S: Because it says the empty spaces in between the wall particles" and "affects their motion," whereas the other one just says the sound is the motion of the wall particles.
I: Uh huh (Yes).
S: Which is not what I would think the sound would be because it's not the particles that started the sound. It's the sound itself.

QUESTION 4

While the interviewer asked follow-up questions related to the choices of Q4, the student developed the Dependent-Independent combination. After reading the answers related to question 4, the student decided she did not like a) and e) and after a pause said:

S: OK. I would think it would be the second one just because that's what I, how I think: it's caused by the sound in between wall particles.
I: OK.
S: So that's what I would answer.
I: Alright.

After follow-up discussion related to this and other choices in question 4 the student said:

S: Actually b) and c) are really close in what they want (sic) in my view.
I: How do you interpret them? How do you interpret the difference between them?
S: This [b)] is caused by the propaganda [propagation], c) is enabled. And that's basically the only difference in between them. So of them says "cause" and one says "enable". It's just how you interpret them I suppose. And I don't know if they'd be a lot different. To me they're so similar in what they say that to me it could be either way

but I chose b) just because it's a cause and effect kind of thing that make a sound go through the wall.
I: OK. In this cause and effect thing, what is first?
S: The cause of the voice s making an effect on the wall.
I: In terms of the motion and sound. What comes first and what comes second in terms of the cause and effect.
S: The motion would come first and [pauses] I mean the sound and then the motion of the wall.
I: OK.
S: The sound is a first
I: So first is sound...
S: Yeah. First is sound. Yeah [Laughs] Like the chicken and the egg. First comes the sound and that comes the vibration through the wall.
I: OK. That's alright. And earlier you told me that air helps or how would you...
S: The air would help it to travel to the wall. I still can't think of the any other way to get there.
I: OK.
S: And the part of it's what's on your picture.
I: Uh huh (Yes).
S: You have a picture and you wrote "air" on both sides of it.
I: Uh huh (Yes).
S: So I figured it must have something to do with it. If that wasn't there I might not have any idea that air had anything to do with it.
I: OK.
S: But also if I haven't had this physics class this semester I might not understand that there's particles there everywhere and that, you know, heat rises...
I: Alright.
S: So I've learned that. Air contributes to something. And so I figured that if it contributes to how air, when it gets heated up it moves, some of that is since this semester started, so I figured it must help move the sound along.
I: OK. So we create sound, sound creates this motion in the air and this motion helps sound to propagate.
S: Right. Right.
I: OK. OK.
S: It just helps it move forward.
I: OK. So that's why you find...and you find b) and c) plausible in this sense.
S: Either one might...and they're so close I mean there's just a one difference in the one sentence.
I: Right. That's right.
S: One is "causing by" (sic) and one is "enabling the" (sic). So I would think it would cause it by (sic) because that's why I picked that one "caused by".
I: And that "enabling the" is also kind of second part, right?
S: Right.
I: So that would be also...
S: Well, you could have a d) on that input. b) and c) would work. [Laughs].
I: Good. Great, I'll actually have to think about it.

S: b) and c) would work together because they actually do work together.
I: Right.

Therefore, as we stated in the introduction to this case, the student's answers in the test reflected both the Independent and Dependent Entity Models in accordance with the student's initial ideas and also according to the Dependent-Independent hybrid she developed during the test.

CASE STUDY No. 5

The student started with the statement that "Sound waves travel through the air" but could not give any explanation for her ideas. She arrived on the Dependent Entity Model during the interviewer's question on propagation through the vacuum.
I: What would be different, if anything, in the situation without air?
S: [Pause]
I: Let's say we eliminate the air. Would that change anything in terms of how sound propagates.
S: Yeah. I would think it certainly would. I mean if they need to travel on, with the...Does the air carry the sound? Is that, um...?
I: So what would you say?
S: Yeah, I would say that the air carries the sound because I know that when air pressure is different it changes how far sound travels. So that would be [un-understandable]
I: OK. And so without air…?
S: Yeah, it wouldn't travel through it.

The student decided in the interview that while the sound propagates the air particles will move "in the direction the sound is going." The following transcript also shows that the sound, air and air movement during the sound propagation are different things.
S: Air particles move when sound is propagated through them.
This reflects entity idea. The following statement defines it as a dependent entity: "air carries the sound. And without that air, there wouldn't be the sound. We wouldn't be hearing it."
In the interview there was also a seed of what will later turn out to be Dependent – Independent combination:
I: So is it [the air movement] kind of consequence or prerequisite or something...
S: The air movement?
I: Yeah.
S: I would think it would be a consequence.

In test question Q1 this student preferred choice e) (which corresponds to both the Dependent and Independent Models) over choice 1c) (which corresponds exclusively to the Dependent Entity Model). She explained that choice c) would correspond to her reasoning if it would say "motion carries the sound..." instead of "motion enables the sound... ."

During the discussion related to question 4, this student developed the Dependent-Independent Hybrid and said that she would like choices 4b and 4c combined.

I: So are you saying it's caused by and then it enables it. What comes first and what comes second.

S: I would say b) would come first, because without the sound there I realize air particles are there first [laughs] completely still but that movement there [described in Q2 and Q3] would… The sound coming through would move it the certain way, and that movement there then would allow it to keep being carried.

In question 5 she was again forced to choose between either the Dependent and Independent Model while she wanted the "package deal" that occurs simultaneously. Her resolution of this problem was surprising because she decided not to pick any of the entity choices but the third one that states that "The motion...occurs at the same time as the sound propagates" although she did not like the second part of the statement "because the described motion of the air particles is the sound."

S: The reason I chose that...

I: You chose d)?

S: Yeah. Um, because of the, this motion is happening at the same time as sound propagates.

I: OK. How about the second part?

S: [Reading] "because the described motion of the air particles is sound". I guess it just depends on of what the definition of sound is. If the motion of air particles enables the sound to be carried then that would be um...

I: Yeah?

S: That would [pause] I'm trying to see if these words should fit my logic that I told you earlier.

I: Please do.

S: They may not. I mean it's...

I: So are you saying that it's primarily this first part that makes this choice attractive?

S: Yeah.

In question 6 the student found the choice pertaining to the Dependent Entity Model (choice a) most plausible because it has the word "carry" to describe the role of the particles of the medium in the sound propagation.

CASE STUDY No. 6

This student had a clear idea of what the sound propagation is and expressed it as an answer to the first interviewer's (open-ended) question. His statement was clearly an Intrinsic Model but the student at first was not able to say anything about the dynamics of the air particles.

S: The speaker is gonna move his vocal cords and then vibrate the air. And this air is gonna travel, this vibrating air is gonna travel to the listener's ear. And when it gets

there it's vibrating in such a pattern that she can pick it up and understand, like translate it back in the words in her brain.
[...]
S: When he is talking he is using his vocal cords to vibrate air and so like that's gonna disturb the air next to it, like the air molecules
I: Alright.
S: and so you know, it's just like a pattern, you know, it disturbs it here and here [shows places more and more away from the listener] and it just keeps going.
I: Alright.
However he didn't know how exactly the air particles move:
I: OK. If you concentrate on individual air particle or particles, how do they move doe to, when sound propagates?
S: [Laughs] I have no idea. I just know they move. Um...I don't know how they move at all.

Nevertheless, the student considered this motion to be intrinsically sound:
I: OK. Is this the same thing or sound and this motion are two different things.
S: I think it's the same thing.

He also correctly said "there is no sound in a vacuum." The answers of this student were all consistent and validly pertaining to the Intrinsic Model.
In question two he picked the choice e) after reasoning through it this way:
S: OK. I'd say yes they do vibrate. Um, so obviously I'd loose up [the choice] a). I don't think it's random because it can't be. Because it has to create specific sounds.
I: Alright.
S: Um [Pause]. [Choices c), d) and e) they all sound good. Like I have, I have absolutely no idea which way it would be or how to figure it, you know.
I: So if this was a real test and if you come to this situation.
S: I guess I'd probably pick e) just because it sounds more likely that they move in both directions.
In question 3:
S: I guess, I don't think air particles actually travel. I mean you can make them but that's not sound. They just, they influence the air particles next to them.
I: OK.
S: So I would have to say that: "No, they don't travel. They only vibrate around the same point without traveling."

This case shows that students who may not know the dynamics of the medium particles on their own may have a rich and valid reasoning for these choices.

In the remaining part of the test he was consistently intrinsic which means the Circular Wave Model in combination with his choices in questions 2 and 3.

CASE STUDY No. 7

During the introduction interview the student explained her reasoning about sound propagation through the wall by stating that the sound wave is fastest on the speaker's side, less fast on the listener's side and the least fast while propagating through the wall. The explanations were:
S: Because the wall is denser than the air.
And
S: Sound waves are vibrations and it's harder to vibrate through the denser objects.

But the student could give no explanation about what the sound wave is or what it is that vibrates. According to the student sound propagation is affected by the wall, but sound also affects the motion of the wall particles. The student could not say in which way the motion of the wall particles is affected except that it is affected less than the air particles when sound propagates through the air.

The following is the student's statement related to the propagation through the vacuum:
I: And tell me what would happen if we wouldn't have any medium, air or wall?
S: Then there would be no sound because they have to go through the medium.
S: Why is that?
S: [Laughs] [Not understandable].
I: Just know it?
S: Yeah
I: That's Alright, where do you know it from?
S: Because light can go through the vacuum and sound can't.
I: So why is it?
S: Because sound needs to have a medium.
[...]
S: Um, I don't know if they really...as sound waves travel in the air, I don't know if they really bounce off the different particles to make the wave...
I: OK.
S: Or they just...I don't know.

There are several ideas expressed here: (1) Entity idea: "as sound waves travel in the air [...] they [...] bounce off the different particles to make the wave." (2) The statement that the sound wave is fastest on the speaker's side, less fast on the listener's side and the least fast while propagating through the wall leans toward the Independent Entity Model. (3) The student's firm statement that there is no sound in the vacuum is aligned with Dependent Entity Model.

Although the student did not clarify the role of the medium she was very firm about the statement that in a vacuum "there would be no sound" and this will reflect on choices that she picked in the test. After the above discussion the student took the test and picked choices that corresponded to the Independent and Dependent Entity Models. This was in agreement with her statements expressed before the test. During the discussion related to question 6 she decided at one point to modify her choice related to that question. The transcripts below show the rationale for the student's answer choices.

In Q1, the student picked choice e) which is a Generic Entity choice (corresponds to both Dependent and Independent Entity Models). She also liked choice 1a) (which is the Independent Entity choice). However, the student preferred choice 1e) because it is more general than the choice a).

S: I would say [Pause], I would say e). But what we talked about before was kind of a combination of a) and e).

This reasoning and the choice reflects not only the student's ideas but also her insecurity about them. In questions 4 and 5 she picked the choices related to the Dependent Entity Model.

This student misinterpreted choice 4b which says that the motion described in Q2 and Q3 (that occurs while sound propagates) "is caused by the propagation of the sound... ." She said that this means that the wall particles do not move at all without the sound propagation. This kind of reading into the statement and assigning alternative meaning to it goes beyond the possibility to be addressed.

In question 6 the student initially picked the choice that corresponds to the Dependent Entity Model (choice a) and later on changed her mind, abandoned choice a) and flipped to choice b. Choice a), although it corresponds to the Dependent Entity Model, does not perfectly reflect her earlier statement that "there would be no sound" in the vacuum.

As the student correctly noticed, the only choice in question 6 that eliminates the possibility that sound *exists* in a vacuum is 6b). So she switched from 6a to 6b and explained her decision this way:

S: Because it [choice 6b)] says, OK [Reads] Sound is the motion of particles of matter [Finishes reading] so if that is true, then [statement] sound can exist in empty space without particles of matter [can not be true]. [The student finishes reading the segment of the choice 6a) and states with emphasis] - It can't. Because it [sound] wouldn't have any matter.

Later in another follow-up explanation of why she eliminated choice 6a) the student said:

S: [Reads 6a)] Sound can exist in empty space without particles of matter. [Finishes reading and states with emphasis] It can't.
I: Alright. So that's why you don't like...[choice 6a)]
S: Yeah. I want that to be can NOT and I would pick a).

So, in a sense of the student's ideas expressed before the test, her choices were valid because her understanding of the sound, although very fuzzy, did not match any of our choices in question 6.

The shift that this student made (away from the dependent choice) made the authors rethink choice 6a), which was in its final version based on the issue raised by this student, but in a greater measure by the student labeled as case No. 13.

CASE STUDY No. 8

This was a straightforward situation in terms of the test validity but complex in terms of the dynamics of the change of the student's models. Namely, the student started with a clear Dependent Entity Model in the interview before the test. Then right before taking the test, the final question triggered another model (Longitudinal Wave) and in the test her choices were consistent with the Wave Model. The transcript below shows that she really did have the Dependent Model during the interview and then changed it right before taking the test. The dialogue below was conducted at the beginning of the interview and it clearly shows the Dependent Entity Model. The first sentence is the student's first answer on the open-ended question about the sound propagation through the wall.

S: I think it would be some particles getting through and some wouldn't.

I: Particles of what? Which particles?

S: I don't know.

I: Well...

S: If sound is made of particles the wall would act as like a filter.

I: OK. What would be the consequence?

S: It wouldn't be...like on the listener's side it would be like muffled.

[...]

S: Um, I guess the wall would...the wall is obviously like a different kind of particle than the sound.

I: OK.

S: And, so it would...like say if like...If these are really big particles and the sound is really small particles (sic.) , it would be easy for the sound to get through.

[...]

I: What would happen if we wouldn't have any of these, air or wall. What would happen in a vacuum, without any particles?

S: Err, there won't be any sound.

I: There will be no sound.

S: Yeah.

I: So why?

S: Because sound...Doesn't sound vibrate...? Sound has to have a medium, doesn't it?

[...]

S: It has to have a medium, because it has to have something to vibrate to make the sound sound (sic).

I: OK. So what would be the role of the medium?

S: To transfer the sound.

I: To transfer the sound. And in this process, does sound propagation affect the motion of the medium particles?

S: [pause]

I: Is motion of the medium particles different when sound propagates and when there is no sound.

S: Yeah.

I: How?

S: Because the sound is creating the vibration whereas when there's no sound there no vibration in the medium.

After this comes the crucial part to understanding what happened with this student in terms of her model dynamics. Up to this point what she expressed was a clear Dependent Entity Model. Because the student specified that the medium particles vibrate differently with and without sound, the interviewer asked about this motion specifically to verify the validity of her choices in the test related to these dynamics (in Q2 and Q3). However, this question triggered a new understanding of the sound propagation and it was the correct Longitudinal Wave Model. It seems that the kinesthetic motion of the student's hand triggered her remembrance of the experiment that she saw in the classroom. She will report on this after the test.
I: OK. Well, I think that's...I think I have everything that I need. Do you possibly know how would the ***medium particles move when there is sound when compared to situation when thee is no sound. How is their motion different when there is sound?***
S: When there is sound?
I: Yeah.
S: Trying to remember. [Pause].. It's like...like that, isn't it? [Waves her hand back and forth horizontally.]
I: Can you say it in words?
S: Like a...like a spring kind of. Like it vibrates...horizontally rather than [Pause] ... I don't remember what kind of wave is it called? It's like a longitudinal or something.
I: Uh huh (Yes). OK.
S: OK. Yeah.

The student took the test after this on her own and in the interviewer's absence. From all that the student said before the test (shown in transcripts above), the interviewer believed that she had a clear Dependent Entity Model with longitudinal vibration of the particles of the medium. To the interviewer's surprise, the student's choices in the test reflected a clear and consistently used Longitudinal Wave Model. And the student was claiming that her answers matched what she was saying earlier:
I: OK. You would basically tell me how did you go about answering these questions. Let me first ask, do you think that what you decided to go with in the test is same, similar or different from what [how] you described the sound earlier.
S: I'd say they are similar. Or probably close to the same.

From this point the student started describing her model as a Wave Model.
I: [Reading question 1] So, how did you go about this one?
S: I thought about, um like my, the previous knowledge that I had and how it's like a vibration. It has to have a medium to travel through.
I: Uh huh (Yes).
S: So, I thought that like um, the motion of the wall particles is the sound because these wall particles is the medium that the sound is traveling through.

Therefore, the main problem in terms of the test validity was that she was stating that her test answers correspond to her earlier model. It was only once and related to question Q1 that she connected the dependent entity test choice with her earlier statements. She said:

S: From what I said earlier I should have picked c). [...] So I was wrong [in my test answers].

But after the interviewer's reassurance that there is nothing wrong with her answers and we are just trying to see how they correspond to her answers before the test, the student firmly adopted her Wave Model and claimed that it was what she was saying earlier too.

The situation was finally resolved when the interviewer played back her statements to the student. This part was recorded with another recorder. After hearing her own earlier statements, the student realized that what she was saying before was the Dependent Entity Model. She also realized that it was the question about the motion of the wall particles that "triggered her memory" and she changed her model.

In the transcript below, the conversation that was heard in the background from the tape player is italicized but not in bold.

S: If sound is made of particles the wall would act as like a filter.
I: OK. What would be the consequence?
S: Yeah. OK. [Tape playing at the background]
I: You see what I mean.
S: Yeah.
[...]
S: OK. I guess the wall would...the wall is obviously like a different kind of particle than the sound
I: OK.
S: And...
S: Yeah. I understand.
I am very confusing. [Laughs] Obviously. [Laughs].
S: ...so it would...like say if like...
S: OK.
If these are really big particles and the sound is...
S: OK. I don't have one.
S: ...really small particles, it would be easy for the sound...
S: Yeah. I don't have one.
S: ...to get through.
S: Yeah. I don't have [not understandable] now.
[...]
S: I completely understand now. OK. [Pause] I was thinking, I don't know, obviously I wasn't I guess, but I was thinking like air was a particle and then when you asked me like later on, remember when you asked me what kind of like wave it was and I said it was longitudinal and that like brought, like it brought it all back to my mind about h.., and I was like Oh! I was completely wrong.
I: Oh. OK.
S: Yeah.
I: OK. OK.
S: Yeah. It was all my fault.

I: This makes sense.
S: I was completely wrong.
I: That makes sense. I mean. But to me this would be like this test is totally messed up. Because...
S: Yeah. It's not the test. It's me. Don't worry [laughs].
I: And if you changed your mind, that's perfectly alright.
S: No. I didn't. I just...You know like sometimes you hear something and it triggers a memory.
I: Right. Right.
S: Yeah. That's what happened to me.
I: That's what I meant. If you changed your mind somewhere along the process, you know.
S: Yeah, it changed before I answered that.
I: Oh. OK.
S: That's why that didn't correspond with that...
I: At the point when I was asking how they move, and when you said back and forth? At that point?
S: Yeah. I was like Uhhhhh [Laughs]. Yeah.
I: Why didn't you tell me that, I mean...[laughs].
S: 'cause I didn't even think about that, totally.
I: Right, right.
S: Until I heard it again.
[...]
I: So you understand now why it was confusing.
S: Yeah. I completely understand why I completely confused you.
[...]
So what exactly did you do in class?
S: She had, it was like a huge spring. And she was just like hit it and you could see...
I: Right, right.
S...you could see like how the longitudinal waves would work.
I: Right, right.
S: And that's why I remembered. I was like chh! The slinky thing!
[...]

This shows not only that a student can change his of her model but also that he or she may be completely unaware of this change.

CASE STUDY No. 9

This is an example when a student is not sure about the model but decides to be self consistent. Student No. 9 initially had the Independent Entity Model as the transcript below shows. The interviewer question was, "How does the sound get on the other side of the wall?"
S: I think that, that it goes through the wall.
I: OK. How?

S: I think by going in between these [drawn particles] air(?)...These are air molecules?
I: These are wall molecules
[...]
I: So sound comes you know, it first propagates through the air and that it reaches the wall.
S: Right. And I think it penetrates the wall. But if it was more dense it would be harder to move through.
I: Why is that?
S: Because there would be more wall molecules maybe and it would stop the move (sic.) of the sound.
I: Alright. What would happen, how would situation be different in the air when compared to wall?
S: If there is no wall?
I: Just here outside in the air, how is the situation different in the air than in the wall? In the air you have the air particles, right?
S: How sound travels in air?
I: Yes, when compared to wall. You said wall affects the sound this way you just described. Would anything be different in air than in wall?
S: Um, I think it's, it's kind of the same, it would just be easier if it was just air. Because I think that maybe air molecules aren't as stationary like they move around easier.
I: OK. How it makes difference?
S: How it makes difference?
I: For sound propagation.

The student here explained that we hear better if there is air between us than if there is a wall between us. When asked about the vacuum she clearly committed to the Independent Entity Model.
I: So what would happen if there would be no air or in a vacuum?
S: Hmm [Pause].
I: So no air or any other material.
S: [Pause].
I: Suppose you put a bell in a vacuum and you kick it. What happens?
S: I don't know. Well, I don't know if sound needs something to grab on to travel. So if there is a vacuum, if there is nothing there...I mean, I guess it would make it easier if there is nothing in a way.
I: OK. And, so easier means like it will travel farther or faster?
S: Both.

While taking the test, the student consistently used her Independent Entity model. In the second reading the student realized that she misread statement 4d) so she did not realize that it is written *air* particles and not sound particles as she wanted. After that she picked choice 4b) which is the Independent Entity Model. However, this case is interesting because it shows that a student may not be sure about the model yet s/he may stick to it consistently. The dialog below shows this situation. It was conducted after the student finished taking the test on her own.

I: So in the first question, you picked choice a). So what was what you liked about it and what you didn't like about others?
S: Um, well I chose a) because that's what I talked about to you before.
I: OK.
S: [Silently] Moves the Particles
I: Uh huh (Yes).
S: And, actually like almost all of these answers I agree with like every single one of them, but I just picked one that I kind of agreed more with. Because they all make sense. But they all kind of contradict themselves. But since I really don't know the right answer, I am like "well it could be that too".
I: OK. So you are saying that from you r standpoint all of them might be true.
S: Yeah.
I: OK. I see. But did you clearly see how they are different.
S: Yeah, I can see the differences.
I: Alright. Alright. I understand what you are saying.

The above discussion shows that it was because of a pure omission that the student did not properly read one of the choices in question 4, which caused the inconsistency.

CASE STUDY No. 10

When student No. 10 was asked the initial question: "...How does sound propagate,?" after a long pause she answered:
S: I don't really know.
I: So, no idea?
S: [Pause] Not really.

This is no model state. After this, in questioning aimed to elicit her ideas, she first expressed thoughts consistent with the Independent Entity Model:
I: That's OK. Let me try to ask you questions that might help you know bring...form something. OK? So do you think this wall would play any role in this propagation of sound?
S: Yeah.
I: So how would it effect or what would be the wall's role in sound propagation?
S: Um, preventing some of the sound waves to travel through.

But her definition of the sound wave was something very close to the Ear-born sound combined with the entity sound in the air. This will be confirmed in the test and in the post-test discussion.
I: Alright. Could you tell me more about sound waves? How do you conceptualize them. What's your understanding of what sound waves are?
S: Um [Pause] errr, produced by us but you can't hear them until they hit your eardrum, and I don't [un-understandable] that's all.

I: OK. Alright. Now tell me would anything be different when sound propagates through the air when compared with the propagation through the wall?
S: Uh huh (Yes).
I: What would be different?
S: They travel easier through air.
I: OK. And why is that?
S: Umm, there is nothing preventing it from traveling through [the air].
I: So, in air you do have the air particles, right?
S: Uh huh (Yes). But they are not as big or distracting the sound waves' match [to the wall particles].
I: OK. So how would air particles be different? How would situation in air be different from situation in the wall when just the particles are concerned?
S: Umm, not as dense.
I: You mean air is not as dense?
S: Uh huh (Yes).

All these ideas are aligned with the Independent Entity Model. The medium is just a larger or smaller obstacle. After this, the vacuum question brought up dependent entity ideas.

I: OK. So what would happen if there would be no particles at all? In vacuum?
S: Sound wouldn't travel?
I: Sound wouldn't travel in vacuum?
S: Yeah.
I: So why is it?
S: It needs the particles to reflect of off. Like...I don't know. It doesn't travel in a vacuum.
I: That's something that you know.
S: Yeah.

Eventually the independent and dependent ideas were put together.

I: OK. So, from that perspective, what would be the role of the particles of medium?
S: It needs some sort of medium but the denser I guess, the harder it gets to travel through it.
I: OK. So is medium something that kind of enables its propagation or...?
S: Uh huh (Yes).

The student couldn't tell anything about the motion of the wall particles.

I: As it propagates, is the motion of these particles in any way affected by sound propagation? Is motion of wall particles different of the same when sound propagates when compared to the situation when there's no sound?
S: I don't know.
[...]

The answers below clarified that this is the entity idea.

I: OK. Let's just make this clear. So these [wall] particles and sound are two different things, or similar things, same thing?

S: Um, different things.
I: So, is sound passing through these particles or in between them?
S: [...] in between them because here's the particles that prevent them [sound waves] from traveling which will be like more the density you get, the less you hear.
I: So, what would you say, it [sound] goes in-between them [the wall particles]?
S: In-between them.

After this discussion, the student took the test and her answer choices reflected Independent, Dependent and Ear-born models. So, they reflected the same mixture that her open-ended answers did.

A few comments are noted here: In question 1 the student first picked choice d), which is the answer corresponding to the propagating air (the propagating air can be associated with either the Independent Entity, Dependent Entity, Ear-born or Intrinsic Model of propagation). Then in the second reading the student modifies her choice and selects choice 1c), which is the Dependent Entity Model. Below is the transcript related to that and it is presented because it indicates that this student overlooked the words "air particles" in choice 1d) and for that reason selected the invalid answer. She corrected herself in the second reading.

I: OK. So how did you go about answering that [question 1]?
S: Since we kind of did the whole thing with it traveling through the particles, then, um...that's how I got this one except I didn't know if it was this one [1d] or this one [1c] because I didn't know about...
I: You didn't know if it's d) or
S: c)
I: c).
S: I guess it would be c) because of the "wall particles move".
I: Uh huh (Yes).
S: And so, it would be c).
I: So this motion enables the sound to travel through the empty spaces?
S: Uh huh (Yes).
I: Ok. So c) would be what you said earlier.
S: Yes.
I: And so why did you [initially] pick d)?
S: I don't know I guess I didn't think through it enough. [...] I guess I just didn't [Pause]. I was more focused on the sound moving in-between the wall particles, then I guess the air particles.
I: This one [1d] also says "through the empty spaces in-between them".
[...]
I: So, are you saying that c) is what corresponds to what you said earlier.
S: Uh huh (Yes).
I: So would you go at this point with c) or d)? Which one seems more plausible?
S: c).
I: c)?
S: Uh huh (Yes).
I: And so in d) you didn't realize that it's about air particles?
S: Yeah

I: OK.

In question 4 this student noticed the air particles and was not tempted by that choice. Here she was not sure between options b and c (Independent and Dependent Models). She also, as did many others, had the problem of picking between "caused by" and "enables" which is earlier mentioned in the "Dependent-Independent" problem.

In question 5, the student misunderstood choice a) in the same way that many others did, i.e. as if it says that the motion of particles of the medium occurs before the speaker starts to speak. This is how the student explained why she eliminated choice 5a):

S: I didn't think that it happened before the sound. 'cause I didn't think that it can be anticipated that it happens.[pause] But between these two...
I: Between c) and d)?
S: Yeah. The reason I think I picked c) is because has "in between them".

So, apparently in Q5 she picked the Independent Entity choice as closest to her reasoning. Because the student expressed independent ideas in her initial open-ended answers, it is not clear if she would have picked choice a) if she understood it as intended. Especially because in question four she also had doubts between the independent and dependent choices. But, it is clear that she did not understand choice 5a) as intended. And the choices that she picked this way do reflect three ideas that she expressed at the beginning. She selected the third initially expressed idea (Ear-born) the first time it was offered in question 6. Here she eliminated answers that started with "Yes" because she knew sound does not propagate in the vacuum. Below is how she explained picking choice 6c) or the Ear-born idea about the nature of the sound.

S: I thought it because of the listener's eardrum part.
I: Uh huh (Yes).
S: And so that's why I picked that one.
I: OK. This one says: [Reading] "Sound is created when moving particles of matter hit the listener's eardrum. Sound does not exist before the listener's eardrum is hit. (A vacuum has no matter so this is not possible)."
I: How this one corresponds to others [your earlier answers]?
S: [Pause] Umm [Pause] Not really. It's not talking about the space that it's traveling through. It's...[Pause]. I don't know.
I: Can you tell me more please.
S: I don't know. I just thought that it didn't happen until you actually heard it. Like that it didn't exist until you, that sound doesn't exist until you hear it.
I: Alright.
S: It doesn't really have to do with the rest of the test, cause it's not talking about...like these talk about this space and the matter that it's traveling through.
[...]
I: Let me try to put it together. In 1 and in 4 you picked these choices that basically say that this motion enables the sound to travel. In 1 and 4.
S: Uh huh (Yes).
I: So you were not really sure about that, right? Or...
S: No, I was not sure.

I: I'm wondering why would you pick [that] then in [questions] one and four and not in [question] 6?
S: Ummm [Pause]
I: You know what I'm asking?
S: Yeah. I don't know. I guess 'cause these were just kind of what we have talked about before. And what we have just kind of been discussing.
I: In 1 and 4?
S: Yeah. But 6 is just kind of something that I've always thought. That sound didn't exist until it hit your eardrum. And so that's why I picked that one [in the question] 6..
I: Oh. OK. OK. And in earlier answers, you didn't have this option.
S: Yeah.
I: OK. I see.
S: Like if we wouldn't have gone through this before, I don't know if I would have had any idea on these at all.
I: In the first five [questions].
S: Uh huh (Yes).
I: OK. And tell me...this idea that you had that the sound doesn't exist before...basically it doesn't exist except in out ear, right?
S: Uh huh (Yes).
I: So what causes it? What happens and we hear sound in ear. What happens in ear and we hear sound.
S: Vibrates the eardrum and...
I: What vibrates the eardrum?
S: The sound waves. The sound.
I: OK. So what would be sound wave?
S: [Pause]
I: Because if sound wave vibrates your eardrum then there is some sound wave outside your eardrum, right?
S: Yeah. [Pause] I don't know. I guess. I don't know. It's just some...[Pause] I don't know.
I: Alright. Basically to my mind it would be possible that either sound creates this, or air particles create this. So if it's sound, then it exists before...I mean it exists outside the ear also, right?
S: Yeah.
I: And if it's air particles....to my mind, that's also possibility. But you didn't like that possibility, right.
S: Yeah. Right. [Laughs].
I: Because you were avoiding those answers with air particles.
S: Yeah. Yeah. [Laughs].
I: And...but then if it's sound, then it does exist outside, right.
S: Yeah. I guess it would.
[...]
I: So you kind of like both ideas. That sound travels...
S: [Laughs]

I: I am very serious. I mean, I don't want to make fun of the answers. So you just like. It seems to me that you just like both ideas. One that it's sound that propagates and another one that sound exist only in our ear. Right?
S: Yeah.
I: Yeah. And that's perfectly legitimate. And that's perfectly legitimate.
S: I guess I don't even know where I got the...that it only occurs when it hits your eardrum. I just think that's something that....I don't know, maybe something that I heard sometime. I mean, I don't know if it's right or not. Maybe it's just the thing that I heard before and that's the only reason I picked the answer.

Later on, after the student in the pictorial representation selected the Dependent Entity Model, the interviewer asked one more question in order to clarify this Entity / Ear-born duality:
I: Is sound in the wall somehow different from the sound that we hear in the ear:
S: I don't know.

This combination of the sound entity in the air and the ear-born sound is not something that we consider compatible but this student apparently liked both at the same time. This is a good example of the usefulness of the test that probes models multiple times and displays model states.

CASE STUDY No. 11

This student did not have any idea about sound propagation at the beginning of the interview and although he expressed several ideas in initial open-ended questions, he did not commit to any of them. However, later during the test taking and discussion he developed a decently refined model (Dependent-Independent Hybrid Model). Here we initially show no model state. After the first question on sound propagation through the air, the answer was following:
S: I suppose they probably travel through the air somehow. 'cause I'm not sure [Pause]. Yeah, my guess is that it has to have something to travel through. Maybe.
I: OK.
S: I don't know. I don't quite know what else.

The other questions in the protocol did not help much because every answer was admittedly a guess and the student was often changing his statements.
I: Do you think air plays or doesn't play a role in this propagation of sound?
S: [Pause, deep breath] I'm gonna guess...it does.
I: So what would be the role of the air?
S: Umm [Pause]. Actually I'm gonna take back my answer [Laughs].
[...]
S: [Pause] I suppose more air resistance might mess it up or maybe if it's really windy, I don't think she'll be able to hear him as good. [...] So it is possible that the air might disturb the propagation of sound.
S: Yeah

I: OK. Do you think that sound affects the motion of air particles when sound propagates or not?
S: Sound affects the motion of air particles? Oh no. I don't think so.
[...]
I: OK. What happens in situation when you don't have the air, in a vacuum, when you don't have any material particles?
S: Hmmm
I: Is it a different situation than in the air? And how, if so?
S: [Pause] I wish I knew more about this. Umm, I don't know. From what I've seen in movies and such, I guess it can't if there is no air. [...] So then obviously air would have something to do with it.
[...]
I: So how is situation different when they [air particles] are there and when they are not there. When there is nothing. For sound propagation?
S: It wouldn't be anything for waves to [Pause]. I guess I don't really know what happens to the waves when they hit the...the particles.
I: Air particles?
S: Yeah.
I: Yeah. OK.
S: If they're bouncing around. I don't know.
I: OK.
S: Or they just go straight through. [Pause]
I: Alright. So basically, waves, if I understand you well, one possibility would be that waves bounce in between these air particles.
S: And maybe that's how they travel.
I: OK. So...and role of the air basically would be just to kind of be an obstacle?
S: [Pause] Yeah.
[...]
I: Uh huh (Yes). OK. And now in light of what you told me, what happens without air particles.
S: That's a good one. [Pause] I guess the sound might not even [Pause] if it does not have anything to travel through it might not be able to travel.
I: So it needs this medium, particles of air to travel?
S: Yeah, I think so.
I: So why it needs...because if they're kind of obstacle and...
S: Still needs this?
I: Yeah.
S: Still needs the obstacles? [Pause] I can't tell you [the answer to] that. [Laughs].

The student took the test on his own and the discussion below was held after it.
I: Can you tell me how did you go about [answering] it [the test].
S: Oh, I kind of went off with what I was trying to say before. It's a written form this time. I kind of found myself trying to answer, trying to circle two of them in few of the questions.
I: OK. So do you think that questions were clear?

S: Yeah, they are clear. [...] I don't know. I just kind of went through and tried to decide which one sounded the most right.

QUESTION 1

I: OK. So in question one, can you tell me why you picked b) and not others? I would ask you this if you picked any of these choices.

S: I wanted to pick this eardrum one that says the sound does not exist before it hits the eardrum. And I don't know if I liked that or not. 'cause I don't know exactly what definition of sound was on there.

I: Alright. How about other choices?

S: Let's see.

S: Sound particles move in a specific manner. I don't know if I like that statement either.

I: Alright.

S: [Pause] This one [1a)] sound, like a lot of these sound right. But I wasn't totally sure so I just picked the one that sounded the most right.

I: You're now talking, you 're showing to 1a). I'm just telling myself.

S: Oh, yeah.

S: A lot of the answers, since I don't know anything about it, any one of them could be right. I could be totally off. For what I don't know. So I just picked the one that sounds the most right to me.

These statements clearly demonstrate no model state. And as far as validity is concerned, no answer is incompatible with this. The student's initial answer to question 4 was along the same lines:

I: How did you go about number 4?

[...]

S: It's just, pretty much what sounded most right to me again.

I: OK.

S: I don' know.

But through the discussion of the choices in Q4 and later Q5 he came up with the Dependent-Independent Model. Below are answers that the student gave during discussion of his choices in question 4:

S: I am pretty sure that it's [air particles] affected by the propagation...that air particles keep affected.

[...]

S: [Pause]...the motion of the air particles...obviously, if they are gonna be in motion, it's gonna be caused by the sound. And it might, that motion might also enable the propagation of the sound. But...

[...]

S: I think the particles...the sound gets the particles moving earlier...whatever the sound is, I guess,

I: Alright, OK.

S: And that once they are moving sound can travel through.

Although he was not very sure about his model, the above transcript reflects a decently developed mechanism of propagation. The student stayed with the dependent entity choice in question 6 by picking choice 6a) but he was still very uncertain:

I: Alright. And in number 6?

S: Yeah. I think that [Pause]. Sound...is it...what exactly would be the definition of sound? Is it that...

I: I'll tell you in a moment.

S: OK. [Laughs ironically with a short exhalation]. Oh, no. I don't think if, I guess what I'm saying is if I was in a vacuum I guess I don't think I would be able to hear somebody talking to me.

CASE STUDY No. 12

This student expressed the Wave Model in open-ended statements and in the graphics. In the test she was consistent with the Wave Model in all questions except in question 1. In this question she misread statement 1e and doubted between choice b) (Intrinsic/Wave choice) and choice 1e) (Independent, Dependent and Phonon choice). Eventually she picked choice 1e. She corrected this when asked about this choice after the test discussion. Thus, the student's final choices were all consistent with her initial model but when she took the test the first time, her choice in Q1 was not. Here we first show that the student had the Wave Model before the test.

I: Our task is to try to describe, as much as you can, how sound propagates in this situation?

[...]

S: Isn't it caused by vibrations that go through the air and reach your ear? And...

I: Alright. When you say vibrations, what exactly do you mean?

S: Um, kind of waves. Like {Pause].

I: Alright. So what would be waves?

[...]

S: The waves are just caused by...they go through the air and they kind of move the particles and [un-understandable] and that's the timber that reaches her ear.

I: Alright. So what are exactly the waves?

S: [Pause]

I: You said waves go through the air so what is it exactly that goes through the air?

S: Energy.

I: Energy, Alright. And can you be more specific in terms of the mechanism. How this energy goes through the air?

S: It's the particles of the air and they keep hitting each other until it reaches your ear.

I: Alright. You were mentioning air particles. What is their role in this story? I mean air or air particles?

S: They carry the wave because without them the sound wouldn't have anything to travel through.

I: Alright, so when sound propagates, does sound propagation effect the motion of air particles at all or not?

S: Yes.

I: In which way?
S: It causes them to vibrate and that's the wave?
I: What's the wave?
S: The vibration of the air particles.
I: OK. Ok so this vibration of the air particles is the wave?
S: I think so [Laughs].
I: Alright. So what happens without air particles, in vacuum? You said...?
S: There is no sound. And this is because there is nothing for the sound to travel through. It doesn't have anything that it can cause to vibrate to travel through.

The student's choices in all test questions were clearly valid except choice 1e, so this discussion will concentrate on that instance.
QUESTION 1
I: So in number one you picked the choice e).
S: Uh huh (Yes).
I: So why e) and not any of these others? What was attractive here and what was...
S: Umm, sound is energy so it doesn't really… it's all consists of matter so like um it propagates through the air by hitting um other...hitting matter.
I: Uh huh (Yes).
S: And that's why I went with e). [As] opposed to ones that said um like moves in-between the air particles, in empty spaces.
I: Like the first one? Through the empty spaces in-between the...
S: Yeah.
[...]
I: How about b)?
S: I don't know. I was kind of stuck between that and e).
I Alright. So why? I mean, what was attractive or not attractive in each of them?
S: [Pause] Um, b) doesn't describe how sound gets from one place to another.
I: Uh huh (Yes). Alright. And e)
S: [Pause] Um, it talks how particles move in a specific manner which would be the sound, but it also explains how it gets from the speaker to the listener.

Choice 1e) describes sound propagation as a process in which "sound particles move in a specific manner. The moving sound particles propagate throughout the air." This student, according to the above transcript, did not consider sound particles as units different from the medium but in a much more correct way. She interpreted "sound particles" in the context of this answer as the air particles' motion, which is sound.
"S: [Pause] Um, it [choice 1e] talks how [air] particles move in a specific manner which would be the sound, but it also explains how it gets from the speaker to the listener."

The researcher's insertion of the word "air" is justified by the following statement that the student wrote in a follow-up communication. After it was verified that the student picked the choices consistent with the Wave Model in all other questions for valid reasons, the interviewer went back to the issue of choice e) in question 1:

I: you know in all these questions like 4,5 and 6 you picked these choices that say that this motion is sound. Right? That this motion is sound?
S: Uh huh (Yes).
I: You told me in number one you were thinking between b and e. Basically b is one that's saying sound is this motion of air particles. Whatever it is, defined basically later but not at this point [yet]. And in e) you have these sound particles that move in a specific manner. So it is one saying how sound gets to the listener too. How did you feel about this wording "sound particles"?
S: I hadn't really noticed that too much [Laughs].
I: OK.
S: Looking back, I don't really like it. Um, it would have been better, it would have made more sense in my mind if it's air particles.
I: So air particles move in a specific manner. Then moving air particles propagate throughout the air. Basically this motion of air particles propagates through the air.
S: Uh huh.

After this conversation the student decided that what she wanted is choice 1b) so this change was not made on her own but rather after a certain prompting on the interviewer's part. After interviewer's follow-up question in the e-mail this was her response:

"Hi,
On the question, why I chose e, is because I failed to notice it properly. I saw the word particle and (incorrectly) assumed it was air particle, failing to notice it was sound particle. That's why I was stuck between two different answers, I thought they were talking about air particles and so answer e more thoroughly described the situation.
Hope this helps!
Signature

This is an example of the need for the Phonon Model in this test. The Phonon Model is what does justice to all of those who have a correct model and understand "sound particles" in a way which is not sound "entity." And this happened in the case of this student. The chances of getting the Phonon Model randomly are 1 in 15,625 in the six question test and 1 in 625 in the four question test, so it is not likely that it will happen by chance.

CASE STUDY No. 13

In case No. 13 the student expressed a clear Wave Model before she took the test. The transcript below confirms that. After the initial question the student drew several particles in a row with a back and forth arrow around them and explained:
S: When he speaks, the air particles vibrate and then this one vibrate, and that it pushes the other one to vibrate, then it pushes the other one to vibrate, and then in the ear, it vibrates the eardrum.
I: I see.

S: So she can hear it.
I: Alright. So basically, when he speaks, this causes this particles close to him to vibrate?
S; Uh huh (Yes).
I: You drew those arrows as vibrating back and forth, like horizontally?
S: Yeah, if he is speaking in that direction.
I: So basically along the direction in which the sound propagates?
S: I guess.
I: OK. And then what happens, this goes from particle to particle, you said, right?
S: Uh huh (Yes).
I: OK. And then?
S: And it hits the eardrum.
I: What hits the eardrum?
S: The vibrate (sic) or the air particles.
I: The vibrating air particles?
S: Affirms nonverbally.
I: OK. So do those air particles vibrate around the same spot or they travel in any direction?
S: They vibrate on the same spot.
I: Alright. Just to make sure, sound in your opinion...\is sound something different from this vibration of the air particles that you described or it is the same thing.
S: I think it is the same thing.
I: That's the sound?
S: Uh huh (Yes)
I: This kind of vibration of the air particles. Alright.
I: And in vacuum what happens when there are no air particles.
S: Then the sound can't transmit to the space...
S: The sound can not transmit because there are...?
S: There's no particles to vibrate.

The answer choices that the student picked in the test were consistent with the Wave Model in all except question 6 where she picked 6a (Dependent Entity Model choice). In section 4.6.1.1. we extensively discussed how this student misinterpreted choice 6a. Here we will briefly repeat that she picked this answer as a correct one and gave the explanation that there has to be a source of sound placed in this vacuum since the question asks whether the sound would propagate or not. If that is the case, then, she argued, sound exists ***within*** that vibrating source. And because there is an empty space around the source, the sound can not propagate. This misinterpretation of the choice was a primary reason and gave us guidance for changes of question 6 made in the post-survey phase of the research.

This student picked the Wave Model also in the pictorial model representation. It should be noted that this student very much liked the Ear-born choices in all of the questions but decided to stick to the intrinsic options because she did not believe sound exists exclusively within the ear-brain system (but that it exists both outside and inside the ear when it is produced).

CASE STUDY No. 14

Student No. 14 did not have a model before she took the test. In the test she was picking what seemed to be the most plausible answer for each of the questions. She clearly understood the answers but was not sure about the right one. The test projected her into the mixed model state and this example shows one of the disadvantages of this multiple-choice instrument – it may assign a model state where there is none. Below are the student's answers on sound propagation given before the test.

S: I don't know. The vibrations in his vocal chords make sound which is between whatever the frequency [range is] that we can hear, and it, I guess these vibrations move through the air and vibrate her [Pause] something [Laughs] and she can hear it. I don't know.
I: The eardrum.
S: OK [Laughs]
I: Alright. So, can you tell me more about the vibration. When you say "vibrations go through the air" or...you said something like that. What do you exactly mean? What are these vibrations?
S: I don't know. [Laughs]
I: Vibrations of what?
S: Um, Ummm. I don't know. I am really don't know, like seriously. Ummm
I: That's alright.
[...]
S: Like air particles. I don't know. [Murmuring misunderstandably to make a joke]. [That suddenly prompts me to ask a new question] Yes? [Laughs]
S&I: [Laughs]
I: So let's put it this way. Do you think the air plays any role or not in this propagation of sound.
The student here said yes and explained that the wind will affect the sound.
I: So what would be its role [of the air]?
S: [Long pause] I don't know. It...I don't know what it is that makes, like I don't know...I don't understand like, OK, I know that her ear, that she now accepts it [receives the sound] but I don't know like what it is that is making it [the eardrum] vibrate. Like, I have no idea.
I: Alright. Do you have any guesses?
S: No. Ummm. Not really. Sorry.
I: So, role of the air again?
S: Ummm, I don't know.
I: If it plays some role, there are only so many possibilities...
S: OK. I'll make a guess. Ummm [Laughs].
I: [Laughs] So, you would say it does play some role?
S: Yeah.
I: What would happen without air? If this was in an empty space?
S: [Long pause]
I: Would anything be different for sound propagation?
S: [Long pause] Yeah. I think [Laughs].

I: So how?
S: Because there would be nothing to make sound vibrate. I don't know. Maybe...I don't know.
I: So air is something that makes sound vibrate?
S: No. Because if you're under a water, there is no air down there but you can still hear.
I: OK. So particles of matter, in general are something that make sound vibrate?
S: Yeah, I guess. That would be my best guess.
I: So, how does it do it? Or how does air accomplish [this]? How does it make sound vibrate?
S: Ummm. I guess like the disruption, like...I don't know. [Laughs]
I: But what. What disrupts what?
S: Ummmm, see I don't know. Like...
I: It's perfectly alright.
S: I don't know. Like what like OK if you have this like...
I: I'm trying to pull out a story from you. You know. Some more or less coherent story.
S: Oh, coherent story.
I: So we know what are the subjects, what are their role, what do they do here...
[...]
I: So what happens in a vacuum?
S: I don't know. I've never been in one [Laughs].
I: That's alright.
S: I would say nothing because I mean, there is nothing that would make your eardrum vibrate.
I: OK. OK. So there is nothing in the vacuum that would make your eardrum vibrate?
S: Yeah.
I: And in the air? In this situation when we have air, what is it that makes the eardrum vibrate?
S: Probably air...particles.
I: Probably air?
S: Particles of air.
I: Particles of air. So what is the relation of particles of air and their motion that causes this vibration of the eardrum with sound?
S: I don't know.
I: Are they related at all?
S: I think so. But I don't know how is it. I don't know. [Laughs]
I: You did such a good job in avoiding the answer which is a trademark of a good student.
[...]
I: Let's just make a story [...]
S: That's basically the only, I mean I'm getting this from the old test like I remember a lot of the questions, maybe not specifically but like the general idea.
I: Right. Let's just try to wrap this up. If you could tell me any idea [about the] role of the air. Because air is causing vibration of the eardrum. That's why she hears. So

what is exactly relationship between this motion of air and sound. What would you guess?
S: I don't know. I mean like the [Pause]
I: But is there...In my mind there are few possibilities. One is that air is just an obstacle. The other one is that air is something... OK. First one is that...Maybe I shouldn't be really telling you the possibilities...

At this point the conversation turned into the multiple-choice test and it can be concluded that there is no model here and all the choices correspond with this. This is a no model state and this is an example of the situation where the tests assigns the models where one essentially does not exist. After the test, the student said that while she was taking the test, in questions 1, 4, 5 and 6 she felt that two, three or all five choices were attractive to her. Specifically, with respect to choice 6b) that she picked (and which was the only correct choice she picked) she told the interviewer:
S: I'm saying that like it doesn't matter to me like which one I pick. Like they both [6b and 6c] sound OK. I could sit here for like ten hours and probably look at the choices and have to just circle one.

When choosing between graphical representations of the models of propagation, the student picked the Propagating Air Model (it corresponds to her choices in questions 2 and 3) along with the ear-born understanding of sound (which is what she picked in questions 4 and 5).

CASE STUDY No. 15

This student expressed the Independent and Dependent Entity Models before she took the test. Sound is a dependent entity in the air and vacuum and independent in the wall. The student was consistent with her models in the test and in the graphical representation of the models.

After a long discussion, on the interviewer's request this student nicely recapitulated her (Independent and Dependent) model in her own words, which enables the author to present it in just a few sentences:
S: The wall molecules have a part in it [the sound propagation]. They move with the sound particles. The sound particles make the wall particles move and they [the wall particles] can be an obstacle depending on how densely they're packed. It [density of the wall particles] limits [the number of] your air particles [that can squeeze in-between the wall particles] so it [the wall] can't carry as much sound [if density is big]. Does that make better sense?
I: So the role of the wall is that it may or may not...
S: Be an...
I: Be an obstacle?
S: Yeah.
I: And the role of the air is that it always helps, or enables the propagation.
S: Yes.

Also of relevance is the student's statement related to the vacuum (expressed before the test) which reveals the crucial role of the air for the propagation of sound:

I: So what happens in a vacuum, in space without any matter?
S: Oh, sound can't propagate because there is nothing there.
I: Alright.
S: There's no air there, in-between the molecules to pass.

In terms of the sound, this is a clear combination of the Dependent Entity Model (pertaining to the air) and Independent Entity Model (pertaining to the wall), which was recombined (hybridized) into a mechanism in which air particles are between the wall particles. This idea solves both "students' classical problems" of the sound propagation through the wall: The fact that sound propagates through it and the fact that sound significantly diminishes after passing through it.

During the test, the student explained why she did not like the dependent entity choices in questions 1, 4 and 5. The transcript below is related to question one. The interviewer's question for the student was what she thought of choice 1c.

S: I didn't really look at the wall particles as enabling the sound. It was more of the air in-between them.
I: [Pause] Ah, OK. So it was the air particles in-between the wall particles...
S: Yes.
I: ...that were enabling the propagation of sound.
S: Yes.
I: Alright.
S: That's why I didn't pick that one.
I: Is this something that you told me earlier? I don't remember you telling me this earlier. Is this something that you...
S: It could have been. Because I know in a vacuum you have to have air to propagate sound. So...
I: So when I asked the question about the vacuum then you...
S: Yeah
I: You thought it might be air that is needed to...
S: Yes.
I: In the case of the wall too?
S: Yes
I: So how about the option 1d)? That basically says that the air particles move all the way through the wall? Is that what you didn't like about it?
S: Yeah.
I: That they move all the way through?
S: Yeah
I: You thought that they just...What exactly did you think?
S: The air particles, I don't think that they move all the way through the wall. They just...
I: But?
S: I think they move, like the wall molecules they might move a little, but I don't think they go all the way through the wall.

I: OK. But if they don't go all the way through the wall that would mean that the wall particles are already filled with air? That it's [the air] already there.
S: Yeah
[...]
S: I would go with that [that the air is already inside].

The graphical representations of the models of propagation also revealed the student's independent and dependent ideas, but she picked the graph corresponding to the Independent Entity Model as one that best describes the sound propagation through the wall.
S: This one is probably closest. The last one. [Independent Entity Model]
I: So where is air here?
S: In-between the wall molecules.
I: So it's the combination of these two (Dependent and Independent)
S: Yea, I guess it would be. See I didn't like that...[Pause] [Deep breath]
I: So basically...OK, you would add air molecules inside here, right?
S: Uh huh (Yes).

CASE STUDY No. 16

This student had a straightforward Dependent Entity Model:
S: I think air particles carry the sound. Motion of waves..
I: Can you please speak up?
S: Air particles carry the waves of the sound. Sound waves are, you know, up and down and these travel through the empty spaces of particles of air. I guess. But air, I mean the motion of these particles does take these sound waves from one position to another.

And accordingly, sound does not propagate in the vacuum.

The test reflected this model in all of the questions except in question 5 where one more time choice 5a) was understood incorrectly in the same way – as if it says that this motion of the particles of the medium occurs before the source creates the sound.
S: I don't like that "precondition" for propagation. It's part of this. Sound causes this motion the motion is not a precondition.
Instead of the Dependent Entity Model, the student picked a choice corresponding to the Independent Entity in Q5.

CASE STUDY No. 17

This student took the test and then the discussion was made before the interviewer took a look at the test results. The conversation displayed that although the student was unsure about her model, it was a rich and developed conceptualization unique among those observed in this and earlier interviews.

According to this model sound is something that is created when sound particles run into the particles of the matter. There is no sound in a vacuum because there is nothing that sound particles would run into. This model in essence boils down to the entity idea with sound being a unit different from the medium. This entity comes close to the dependent entity idea because in order for sound to be created sound particles are not enough but they need the medium too. There is no sound in the vacuum because, as the student says, "in a vacuum when there aren't any particles you can't hear the sound because it's not running into anything." Sound "running into something" also indicated the independent entity idea. However, when graphical representations of the most common models were presented to her, this student picked the Dependent Entity Model as being closest to the one that she is using. Accordingly, she picked the Dependent Entity Model choices throughout the test except in question 5 where she was attracted by the statement "occurs at the same time" in choice 5d). She picked this choice although she did not like the second part of the same statement. Below we first show the evidence of the student's uncertainty about her model:

I: What happens and this guy hears the sound? What is the mechanism?

S: [Long pause] I don't know.

I: You don't know. OK. That's fair enough. Tell me how did you go about taking the test?

S: I just looked at the answers and picked, [Laughs] pickled which I think would be the best.

Evidence of the model:

I: Alright. So basically now after taking the test, could you summarize what you believe you picked there?

S: Umm, that the particles move, that the sound particles have to run into the wall particles to make the sound and so that they move and the wall particles move too.

I: What is the role of the movement? Is it that sound particles created this motion of the wall particles or it's the motion of the wall particles that kind of carries the sound, or...

S: The wall carries the sound.

I: Wall carries the sound.

S: Yeah.

Below is that statement with the follow -up that shows two important things. (1) Although students' models are sometimes very sophisticated, they may be very shaky at the same time. (2) The complexity and uniqueness of the model expressed by this student shows one more time that possible variations in students' understandings are limitless and we will never be able to make ideal choices for all possible students' ideas. But, as shown in these interviews as a whole, there are several basic ideas upon which all of the models are built. Student No. 17 offered the statement below as her ideal answer for question 5:

S: There isn't sound until it hits the wall particle.

I: Until what hits the wall particle?

S: Until the sound particle runs into the wall particle. And so I don't think there's a motion of the wall particle until that happens.

I: OK. But you said there is no sound before that happens?
S: Right.
I: So what is the difference between the sound and the sound particle?
S: [Pause] I don't know. [Laughs]
I: You know what I'm asking. If sound particle hits the wall, then, you know, then there is sound particle. But you said there is no sound. So how would you explain.
S: Sound could not be heard until it runs into something.
I: Sound could not be heard until it runs into something. Can you tell me more about this? Please.
[...]
S: Like, 'cause, 'cause in a vacuum when there aren't any particles you can't hear the sound because it's not running into anything. That's what I thought.
I: Because sound particles are not running into it.
S: Right.
I: Is that what you are saying?
S: Uh huh (Yes).
I: Because what we hear is this sound of this [Pause] collision basically or...is that sound that we hear is... Tell me please more. I would really like to understand.
S: [Laughs, Sighs]
I: So sound particles hit the particles of the wall or whatever and why we hear that?
S: I don't know.
I: I mean what is it that we hear exactly? This kind of collision of those two or what?
S: The sound particle has to have something to vibrate against something.
I: OK. So sound particle vibrates against something? Vibrates against something. Can you please clarify that?
S: [Laughs, Sighs]
I: What does it exactly mean? Is that that they kind of rub on each other or like rub against each other or..?
S: Yeah, when they hit each other.
I: And this is what we hear?
S: Yeah.

There is another interesting statement that this student gave which is very important from the perspective of determining the validity of the probe. It shows that test taking is not a simple mapping of the pre-existing answers or models, but rather a dynamic process. This appendix was needed because of the complexity of this process. Below is the statement:

I: When you were taking the test do you think that after reading the question you were able to...um do you think you had a ready answer and then you tried to find it in the choices...?
S: No.
I: No. OK. So what did you do?
S: I would flip the choices and then pick which one I thought would be the best answer.

APPENDIX O
CORRELATIONS BETWEEN THE TEST ANSWER CHOICES

Table O.1.
Correlations between answer choices; All colleges; AIR Context; N=1151

	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e	6a	6b	6c	6d	6e
1a	**1.00**																													
1b	**-0.24**	**1.00**																												
1c	**-0.14**	**-0.26**	**1.00**																											
1d	**-0.18**	**-0.35**	**-0.20**	**1.00**																										
1e	**-0.20**	**-0.38**	**-0.21**	**-0.29**	**1.00**																									
2a	0.03	0.00	-0.04	0.00	0.00	**1.00**																								
2b	0.02	-0.05	0.06	-0.06	0.04	**-0.07**	**1.00**																							
2c	-0.03	**0.21**	-0.01	-0.04	**-0.16**	**-0.12**	**-0.24**	**1.00**																						
2d	-0.05	-0.05	-0.02	**0.09**	0.03	**-0.07**	**-0.14**	**-0.24**	**1.00**																					
2e	0.03	**-0.13**	0.00	0.02	**0.11**	**-0.16**	**-0.32**	**-0.56**	**-0.32**	**1.00**																				
3a	**0.08**	-0.05	-0.02	0.01	0.00	**0.31**	0.03	-0.05	-0.04	-0.06	**1.00**																			
3b	-0.01	**0.20**	**-0.08**	0.01	**-0.15**	**-0.11**	**-0.12**	**0.30**	0.02	**-0.17**	**-0.08**	**1.00**																		
3c	-0.05	-0.02	**0.11**	-0.03	0.01	-0.04	0.01	0.00	0.06	-0.03	**-0.06**	**-0.36**	**1.00**																	
3d	0.04	**-0.11**	-0.02	0.02	**0.09**	0.00	**0.08**	**-0.20**	-0.02	**0.15**	**-0.08**	**-0.47**	**-0.37**	**1.00**																
3e	-0.01	**-0.07**	0.02	0.00	**0.07**	**0.09**	0.04	**-0.12**	-0.05	**0.09**	-0.05	**-0.26**	**-0.20**	**-0.27**	**1.00**															
4a	0.03	**-0.08**	-0.01	-0.01	**0.08**	**0.22**	0.04	-0.06	-0.01	-0.04	**0.25**	**-0.07**	-0.03	-0.03	**0.09**	**1.00**														
4b	**0.13**	**-0.11**	**0.06**	**-0.12**	**0.09**	-0.05	**0.06**	**-0.06**	0.00	0.03	0.00	-0.05	**0.14**	-0.02	**-0.07**	**-0.12**	**1.00**													
4c	0.04	**-0.12**	**0.13**	**-0.08**	**0.07**	-0.01	0.02	-0.03	-0.02	0.04	0.00	0.00	-0.03	-0.01	0.06	**-0.11**	**-0.34**	**1.00**												
4d	**-0.09**	**-0.22**	**-0.08**	**0.50**	**-0.11**	-0.01	-0.03	-0.03	**0.09**	-0.01	-0.05	-0.03	-0.05	**0.07**	0.03	**-0.09**	**-0.26**	**-0.25**	**1.00**											
4e	**-0.11**	**0.42**	**-0.12**	**-0.20**	**-0.10**	-0.02	**-0.07**	**0.15**	-0.05	-0.05	-0.06	**0.11**	-0.05	-0.01	-0.04	**-0.13**	**-0.39**	**-0.36**	**-0.28**	**1.00**										
5a	**0.11**	**-0.07**	-0.01	-0.06	0.06	-0.02	0.05	**-0.07**	-0.02	0.05	0.01	**-0.07**	-0.02	**0.07**	0.02	-0.02	0.05	**0.11**	-0.05	**-0.10**	**1.00**									
5b	-0.05	**-0.24**	-0.05	**0.48**	**-0.12**	-0.03	-0.03	-0.02	0.03	0.03	-0.03	0.01	-0.01	0.04	-0.03	0.00	**-0.14**	-0.04	**0.43**	**-0.17**	**-0.10**	**1.00**								
5c	**0.15**	**-0.17**	**0.15**	**-0.13**	**0.09**	-0.06	0.01	-0.02	-0.03	0.05	-0.01	-0.02	0.03	0.00	0.00	-0.04	**0.33**	**0.10**	**-0.14**	**-0.28**	**-0.14**	**-0.29**	**1.00**							
5d	**-0.14**	**0.39**	**-0.09**	**-0.19**	-0.06	-0.02	-0.03	**0.12**	0.04	**-0.10**	**-0.07**	**0.10**	0.02	**-0.07**	-0.05	**-0.09**	**-0.18**	**-0.13**	**-0.14**	**0.45**	**-0.18**	**-0.37**	**-0.56**	**1.00**						
5e	0.00	-0.04	-0.02	-0.02	**0.09**	**0.18**	0.05	**-0.10**	-0.04	0.02	**0.20**	**-0.10**	-0.05	0.01	**0.12**	**0.28**	**-0.09**	0.03	-0.04	-0.03	-0.06	**-0.12**	**-0.18**	**-0.23**	**1.00**					
6a	0.06	**-0.11**	0.04	-0.04	**0.08**	-0.03	0.00	-0.05	-0.01	**0.07**	-0.02	-0.03	0.03	0.00	0.01	0.00	**0.11**	**0.11**	-0.06	**-0.16**	0.06	-0.02	**0.15**	**-0.15**	0.00	**1.00**				
6b	**-0.13**	**0.30**	-0.04	**-0.10**	**-0.10**	-0.06	-0.02	**0.18**	0.01	**-0.14**	**-0.08**	**0.18**	**-0.08**	-0.04	**-0.07**	-0.05	**-0.12**	-0.06	**-0.11**	**0.28**	**-0.11**	**-0.17**	**-0.11**	**0.29**	-0.04	**-0.57**	**1.00**			
6c	0.00	**-0.17**	-0.04	**0.33**	**-0.10**	0.00	0.01	-0.02	-0.01	0.02	-0.01	-0.02	-0.04	0.02	0.05	0.01	**-0.08**	**-0.08**	**0.36**	**-0.14**	-0.03	**0.37**	**-0.09**	**-0.16**	-0.04	**-0.21**	**-0.30**	**1.00**		
6d	**0.07**	**-0.10**	0.06	-0.05	0.05	**0.08**	-0.01	**-0.08**	0.00	0.05	**0.12**	**-0.14**	**0.12**	0.02	-0.02	0.05	**0.07**	0.04	**-0.06**	**-0.07**	**0.08**	0.00	0.02	-0.06	0.02	**-0.20**	**-0.29**	**-0.11**	**1.00**	
6e	**0.07**	**-0.09**	0.00	-0.06	**0.10**	0.06	0.03	**-0.12**	0.00	**0.07**	**0.08**	**-0.10**	0.01	0.03	**0.07**	0.05	**0.07**	-0.03	-0.05	-0.01	0.05	**-0.07**	0.04	-0.05	**0.09**	**-0.18**	**-0.26**	**-0.10**	**-0.09**	**1.00**

Sig. levels for N=1000
0.062 at 5% level two tailed – **bold font**
0.081 at 1% level two tailed - **bold and underlined font**

Table O.2.
Correlations between answer choices; All High Schools; AIR Context; N=236

	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e	6a	6b	6c	6d	6e
1a	**1.00**																													
1b	**-0.20**	**1.00**																												
1c	**-0.17**	**-0.21**	**1.00**																											
1d	**-0.22**	**-0.28**	**-0.24**	**1.00**																										
1e	**-0.24**	**-0.31**	**-0.26**	**-0.35**	**1.00**																									
2a	**0.14**	0.02	-0.05	-0.07	-0.01	**1.00**																								
2b	0.06	0.06	-0.02	-0.07	-0.01	-0.06	**1.00**																							
2c	-0.04	0.02	-0.09	**0.16**	-0.06	-0.09	**-0.34**	**1.00**																						
2d	-0.04	0.09	**0.16**	-0.01	**-0.16**	-0.05	**-0.19**	**-0.27**	**1.00**																					
2e	-0.02	-0.13	0.01	-0.06	**0.19**	-0.09	**-0.34**	**-0.49**	**-0.28**	**1.00**																				
3a	0.04	0.00	-0.03	-0.07	0.06	**0.30**	0.00	-0.10	0.11	-0.06	**1.00**																			
3b	0.02	**0.18**	-0.08	0.06	**-0.18**	-0.09	-0.10	**0.32**	0.00	**-0.21**	**-0.14**	**1.00**																		
3c	0.03	**-0.16**	0.01	0.06	0.06	-0.07	0.08	-0.02	0.07	-0.07	-0.11	**-0.36**	**1.00**																	
3d	0.02	-0.04	0.05	-0.01	0.00	-0.08	0.02	**-0.17**	-0.11	**0.25**	**-0.14**	**-0.44**	**-0.34**	**1.00**																
3e	-0.11	0.00	0.06	-0.10	**0.13**	**0.15**	0.01	**-0.13**	0.00	0.08	-0.08	**-0.26**	**-0.20**	**-0.25**	**1.00**															
4a	0.06	0.10	0.00	-0.06	-0.07	**0.24**	0.02	-0.06	0.06	-0.06	**0.21**	-0.06	0.00	-0.04	0.01	**1.00**														
4b	0.09	-0.11	**0.16**	-0.13	0.02	0.01	-0.07	0.03	0.04	0.00	-0.11	-0.05	0.04	0.09	-0.05	**-0.13**	**1.00**													
4c	0.09	-0.07	0.12	**-0.15**	0.04	-0.01	0.01	-0.11	0.04	0.07	0.01	-0.09	-0.08	0.06	**0.13**	**-0.15**	**-0.32**	**1.00**												
4d	**-0.13**	**-0.17**	**-0.15**	**0.42**	-0.04	-0.06	0.09	-0.05	-0.03	0.01	0.00	0.05	0.05	-0.03	-0.09	-0.12	**-0.26**	**-0.30**	**1.00**											
4e	-0.09	**0.28**	**-0.13**	-0.10	0.02	-0.08	-0.03	**0.16**	-0.08	-0.06	-0.02	**0.13**	0.00	-0.11	-0.01	**-0.14**	**-0.30**	**-0.36**	**-0.28**	**1.00**										
5a	0.00	-0.02	-0.06	-0.05	0.12	-0.04	**0.24**	**-0.14**	-0.04	-0.02	0.07	0.02	0.07	-0.12	0.00	-0.08	-0.03	**0.15**	0.05	-0.12	**1.00**									
5b	-0.05	**-0.14**	-0.07	**0.45**	**-0.21**	-0.06	-0.05	0.09	0.05	-0.06	0.01	-0.05	0.00	0.10	-0.07	-0.02	-0.10	-0.08	**0.31**	-0.11	**-0.15**	**1.00**								
5c	**0.16**	**-0.17**	**0.21**	**-0.25**	0.10	-0.02	0.00	-0.04	0.01	0.03	-0.05	-0.04	0.09	0.03	-0.06	**-0.13**	**0.21**	0.10	**-0.14**	-0.09	**-0.22**	**-0.31**	**1.00**							
5d	-0.08	**0.38**	**-0.18**	-0.03	-0.10	-0.02	-0.11	**0.14**	-0.02	-0.03	**-0.14**	**0.15**	-0.05	-0.03	-0.04	0.03	-0.02	-0.10	**-0.17**	**0.27**	**-0.22**	**-0.31**	**-0.45**	**1.00**						
5e	-0.06	-0.10	0.09	-0.10	**0.16**	**0.17**	0.01	**-0.15**	-0.01	0.11	**0.20**	**-0.15**	-0.12	-0.01	**0.24**	**0.26**	-0.11	-0.03	0.00	-0.01	-0.11	**-0.16**	**-0.23**	**-0.23**	**1.00**					
6a	**0.14**	**-0.14**	0.01	-0.07	0.07	0.13	-0.06	-0.02	-0.01	0.04	-0.05	0.05	-0.08	0.00	0.05	-0.09	0.04	**0.17**	-0.04	**-0.14**	-0.03	0.02	0.06	-0.04	-0.05	**1.00**				
6b	-0.08	**0.28**	-0.08	-0.04	-0.08	-0.10	-0.04	**0.13**	0.00	-0.07	-0.02	0.11	-0.01	0.01	**-0.15**	0.00	-0.06	-0.12	-0.12	**0.29**	-0.09	**-0.17**	-0.03	**0.31**	-0.11	**-0.48**	**1.00**			
6c	-0.10	-0.01	-0.04	**0.26**	**-0.13**	-0.05	-0.04	0.09	-0.02	-0.03	0.12	0.07	-0.03	-0.03	-0.10	0.02	-0.12	-0.01	**0.26**	-0.12	0.02	**0.36**	**-0.15**	-0.13	-0.04	**-0.24**	**-0.26**	**1.00**		
6d	0.10	-0.07	0.04	-0.04	0.00	0.06	0.07	**-0.13**	0.02	0.04	-0.01	**-0.15**	**0.20**	-0.05	0.03	0.08	0.01	0.06	-0.07	-0.05	0.11	-0.02	0.03	-0.12	0.05	**-0.23**	**-0.26**	-0.13	**1.00**	
6e	-0.07	-0.12	0.10	-0.06	**0.14**	-0.05	0.11	-0.12	0.01	0.04	-0.01	**-0.14**	-0.04	0.04	**0.21**	0.02	**0.15**	-0.12	0.04	-0.07	0.05	-0.10	0.08	**-0.17**	**0.21**	**-0.25**	**-0.28**	**-0.13**	**-0.13**	**1.00**

Sig. levels for N=236
0.129 at 5% level two tailed – **bold font**
0.1691 at 1% level two tailed – **bold and underlined font**

Table O.3.
Correlations between answer choices; All Middle Schools; AIR Context; N=64

	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e	6a	6b	6c	6d	6e
1a	**1.00**																													
1b	-0.10	**1.00**																												
1c	-0.10	-0.19	**1.00**																											
1d	-0.18	**-0.36**	**-0.36**	**1.00**																										
1e	-0.12	-0.24	-0.24	**-0.46**	**1.00**																									
2a	0.18	0.01	0.16	-0.05	-0.18	**1.00**																								
2b	0.02	0.00	0.00	-0.19	0.21	-0.21	**1.00**																							
2c	-0.11	0.10	-0.11	**0.29**	**-0.28**	-0.16	**-0.33**	**1.00**																						
2d	-0.11	-0.11	-0.11	0.06	0.18	-0.16	**-0.33**	**-0.25**	**1.00**																					
2e	0.07	0.00	0.10	-0.10	0.00	-0.16	**-0.33**	**-0.25**	**-0.25**	**1.00**																				
3a	-0.04	0.17	0.17	-0.15	-0.10	**0.25**	0.08	-0.09	-0.09	-0.09	**1.00**																			
3b	-0.07	-0.14	-0.14	0.06	0.20	-0.10	0.03	-0.03	0.10	-0.03	-0.06	**1.00**																		
3c	0.16	0.16	-0.03	-0.17	0.01	0.00	-0.16	0.23	-0.10	0.06	-0.13	-0.22	**1.00**																	
3d	-0.03	-0.17	-0.08	**0.32**	-0.14	0.07	0.04	-0.01	-0.01	-0.09	-0.14	**-0.26**	**-0.56**	**1.00**																
3e	-0.10	0.05	0.17	-0.18	0.07	-0.14	0.10	-0.22	0.10	0.10	-0.08	-0.14	**-0.30**	**-0.34**	**1.00**															
4a	-0.04	-0.08	-0.08	0.03	0.11	-0.06	**0.28**	-0.09	-0.09	-0.09	-0.03	-0.06	-0.13	0.22	-0.08	**1.00**														
4b	-0.10	0.17	-0.07	-0.01	-0.03	-0.14	0.00	0.00	0.10	0.00	-0.08	-0.14	-0.12	0.01	**0.29**	-0.08	**1.00**													
4c	0.03	-0.06	0.13	-0.14	0.08	-0.19	-0.16	0.05	0.05	0.22	-0.11	0.17	0.03	-0.05	-0.06	-0.11	**-0.26**	**1.00**												
4d	-0.17	-0.14	-0.23	**0.44**	-0.11	-0.02	0.01	0.11	0.03	-0.14	0.05	0.09	0.10	-0.07	-0.14	-0.13	**-0.32**	**-0.45**	**1.00**											
4e	**0.27**	0.12	0.23	**-0.40**	0.02	**0.39**	0.04	-0.14	-0.14	-0.04	0.14	-0.15	0.01	0.03	0.01	-0.09	-0.21	**-0.29**	**-0.36**	**1.00**										
5a	-0.06	0.04	-0.13	0.11	-0.02	-0.09	0.07	0.00	-0.15	0.14	-0.05	-0.09	0.04	0.01	0.04	-0.05	0.04	-0.04	0.02	0.01	**1.00**									
5b	-0.16	-0.13	-0.13	**0.27**	-0.01	0.22	-0.04	-0.04	0.13	-0.20	0.06	-0.01	-0.09	0.09	-0.04	0.06	**-0.31**	-0.21	**0.55**	-0.18	-0.21	**1.00**								
5c	**0.34**	0.10	0.10	-0.12	-0.20	0.03	0.03	-0.07	0.01	0.01	-0.12	-0.09	-0.16	0.11	0.19	-0.12	**0.47**	-0.16	**-0.42**	**0.30**	-0.19	**-0.47**	**1.00**							
5d	-0.08	0.12	-0.01	-0.19	0.16	-0.11	0.10	0.07	-0.18	0.07	0.22	-0.11	0.18	-0.18	-0.01	-0.06	-0.01	0.24	-0.16	-0.04	-0.10	**-0.25**	-0.23	**1.00**						
5e	-0.10	-0.08	0.15	-0.12	0.14	-0.15	-0.11	0.08	0.08	0.08	-0.08	**0.28**	0.12	-0.11	-0.20	0.16	-0.20	**0.29**	-0.08	-0.11	-0.13	**-0.33**	**-0.30**	-0.16	**1.00**					
6a	-0.20	-0.12	0.14	0.04	0.03	0.15	-0.02	0.10	-0.05	-0.13	0.02	**-0.28**	**-0.35**	**0.33**	0.23	-0.16	0.14	-0.17	-0.07	0.22	-0.02	0.09	0.19	-0.01	**-0.32**	**1.00**				
6b	**0.55**	0.07	0.07	-0.15	-0.22	0.02	-0.07	-0.09	0.02	0.13	-0.07	0.02	**0.29**	-0.23	-0.05	-0.07	0.07	0.16	-0.21	0.04	-0.12	-0.20	**0.33**	-0.14	0.05	**-0.36**	**1.00**			
6c	-0.14	0.00	-0.19	0.09	0.12	-0.09	0.10	-0.16	0.18	-0.07	0.08	0.14	0.20	-0.10	**-0.28**	0.08	-0.19	0.00	**0.30**	-0.22	0.07	0.18	**-0.42**	-0.01	**0.25**	**-0.57**	**-0.26**	**1.00**		
6d	-0.06	**0.24**	-0.11	-0.08	0.01	-0.08	-0.03	-0.13	-0.13	**0.35**	-0.05	0.14	-0.04	-0.21	**0.24**	-0.05	-0.11	0.14	-0.06	0.04	0.17	-0.19	-0.03	0.12	0.05	-0.23	-0.10	-0.17	**1.00**	
6e	-0.06	-0.11	0.07	0.05	0.01	-0.08	-0.03	**0.35**	-0.13	-0.13	-0.05	0.14	-0.04	0.06	-0.11	**0.32**	0.07	-0.01	-0.06	-0.12	-0.08	-0.05	-0.03	0.12	0.05	-0.23	-0.10	-0.17	-0.07	**1.00**

Sig. levels for N=64
0.243 at 5% level two tailed – **bold font**
0.316 at 1% level two tailed – **bold and underlined font**

Table O.4.
Correlations between answer choices; All Colleges; WALL Context; N=429

	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e	6a	6b	6c	6d	6e
1a	**1.00**																													
1b	**-0.21**	**1.00**																												
1c	**-0.17**	**-0.19**	**1.00**																											
1d	**-0.24**	**-0.27**	**-0.22**	**1.00**																										
1e	**-0.27**	**-0.30**	**-0.24**	**-0.34**	**1.00**																									
2a	**0.10**	-0.09	-0.03	-0.01	0.03	**1.00**																								
2b	0.05	-0.08	0.00	0.06	-0.01	-0.07	**1.00**																							
2c	-0.09	**0.24**	-0.05	-0.03	-0.07	**-0.11**	**-0.25**	**1.00**																						
2d	0.02	0.08	-0.05	-0.02	-0.03	-0.06	**-0.13**	**-0.19**	**1.00**																					
2e	-0.01	**-0.16**	0.09	0.00	0.08	**-0.17**	**-0.38**	**-0.57**	**-0.29**	**1.00**																				
3a	0.07	-0.09	-0.07	0.09	-0.02	**0.50**	0.04	**-0.11**	-0.06	-0.08	**1.00**																			
3b	**-0.11**	**0.18**	0.01	-0.01	-0.06	**-0.12**	-0.01	**0.11**	**0.17**	**-0.14**	**-0.19**	**1.00**																		
3c	**0.12**	-0.02	0.00	-0.02	-0.05	-0.07	-0.03	0.08	-0.04	-0.01	-0.07	**-0.41**	**1.00**																	
3d	-0.07	**-0.10**	-0.01	0.04	**0.12**	0.05	-0.06	**-0.11**	**-0.15**	**0.21**	-0.08	**-0.53**	**-0.18**	**1.00**																
3e	0.09	**-0.10**	0.04	-0.06	0.03	-0.07	0.09	-0.06	-0.01	0.02	-0.06	**-0.39**	**-0.13**	**-0.17**	**1.00**															
4a	-0.03	-0.05	0.02	0.04	0.02	0.06	**0.12**	0.00	-0.04	-0.08	**0.24**	-0.02	-0.09	-0.07	**0.10**	**1.00**														
4b	**0.11**	**-0.21**	0.05	**-0.12**	**0.17**	-0.02	0.02	**-0.10**	0.03	0.07	**-0.11**	-0.03	0.06	0.04	0.00	**-0.16**	**1.00**													
4c	-0.02	**-0.12**	**0.15**	0.05	-0.03	-0.04	-0.03	-0.01	-0.02	0.05	-0.04	0.01	0.03	0.01	-0.04	**-0.14**	**-0.35**	**1.00**												
4d	0.05	**-0.21**	-0.09	**0.26**	-0.03	**0.12**	0.05	-0.01	-0.07	-0.03	**0.10**	-0.09	0.01	0.02	0.06	**-0.14**	**-0.33**	**-0.30**	**1.00**											
4e	**-0.14**	**0.61**	**-0.13**	**-0.21**	**-0.13**	-0.09	**-0.12**	**0.13**	0.09	-0.05	-0.09	**0.13**	-0.04	-0.03	-0.07	**-0.13**	**-0.31**	**-0.28**	**-0.27**	**1.00**										
5a	0.06	-0.02	-0.02	0.01	-0.03	-0.04	-0.06	-0.03	-0.07	**0.12**	0.03	-0.05	0.06	0.01	0.00	0.04	0.02	0.06	-0.06	-0.05	**1.00**									
5b	-0.03	**-0.21**	-0.04	**0.16**	0.09	0.02	0.04	-0.03	-0.02	0.01	-0.07	-0.02	0.01	0.04	0.01	-0.07	-0.05	-0.02	**0.31**	**-0.20**	**-0.12**	**1.00**								
5c	**0.15**	**-0.21**	0.06	-0.05	0.07	**-0.10**	0.02	-0.04	0.02	0.04	-0.07	-0.01	-0.02	0.08	-0.02	**-0.10**	**0.30**	0.04	-0.05	**-0.27**	**-0.15**	**-0.40**	**1.00**							
5d	**-0.16**	**0.48**	-0.04	**-0.16**	**-0.11**	-0.05	-0.06	**0.15**	0.05	**-0.10**	-0.08	**0.12**	-0.02	-0.07	-0.05	0.02	**-0.17**	**-0.13**	**-0.23**	**0.55**	**-0.13**	**-0.35**	**-0.44**	**1.00**						
5e	0.02	-0.07	0.04	0.07	-0.05	**0.23**	0.03	-0.09	-0.03	-0.01	**0.29**	-0.09	0.01	-0.09	0.09	**0.20**	**-0.15**	**0.11**	0.01	-0.08	-0.07	**-0.19**	**-0.25**	**-0.21**	**1.00**					
6a	-0.02	**-0.11**	0.07	0.07	0.00	-0.03	-0.02	-0.02	**-0.11**	**0.11**	-0.02	-0.07	-0.03	**0.13**	-0.01	0.01	0.00	0.03	0.06	**-0.10**	0.01	-0.07	0.02	-0.03	**0.10**	**1.00**				
6b	**-0.11**	**0.29**	-0.09	0.01	**-0.11**	0.06	-0.02	0.06	**0.11**	**-0.12**	0.02	**0.15**	-0.04	**-0.15**	-0.02	-0.05	-0.09	-0.05	-0.06	**0.25**	-0.09	-0.03	-0.09	**0.20**	-0.06	**-0.52**	**1.00**			
6c	0.04	-0.07	-0.01	-0.03	0.03	0.02	-0.02	0.03	0.01	-0.02	0.02	-0.03	0.02	0.05	-0.04	0.03	-0.03	0.08	0.00	-0.07	0.06	0.03	0.01	-0.06	-0.01	**-0.23**	**-0.30**	**1.00**		
6d	0.05	**-0.12**	0.05	-0.02	0.05	-0.06	0.02	-0.06	-0.02	0.08	-0.01	**-0.12**	**0.11**	0.04	0.03	0.05	**0.16**	-0.04	-0.05	**-0.11**	0.08	0.07	0.08	**-0.15**	-0.04	**-0.21**	**-0.28**	**-0.12**	**1.00**	
6e	**0.10**	**-0.11**	-0.02	-0.07	**0.11**	-0.01	0.09	-0.04	-0.01	-0.02	-0.01	0.00	-0.01	-0.04	0.08	-0.01	0.03	-0.02	0.05	-0.07	-0.03	0.06	0.01	-0.06	0.00	**-0.19**	**-0.25**	**-0.11**	**-0.10**	**1.00**

Sig. levels for N=429
0.0951 at 5% level two tailed – **bold font**
0.12423 at 1% level two tailed – **bold and underlined font**

Table O.5.
Correlations between answer choices; All High Schools; WALL Context; N=166

	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e	6a	6b	6c	6d	6e
1a	**1.00**																													
1b	**-0.23**	**1.00**																												
1c	**-0.19**	**-0.24**	**1.00**																											
1d	**-0.27**	**-0.33**	**-0.28**	**1.00**																										
1e	**-0.20**	**-0.25**	**-0.21**	**-0.29**	**1.00**																									
2a	-0.02	**-0.17**	-0.14	**0.18**	0.13	**1.00**																								
2b	0.03	-0.12	0.01	**0.19**	-0.14	-0.12	**1.00**																							
2c	-0.03	**0.36**	-0.05	**-0.17**	-0.10	**-0.21**	**-0.26**	**1.00**																						
2d	-0.08	0.07	0.14	0.01	-0.15	-0.13	**-0.16**	**-0.27**	**1.00**																					
2e	0.08	**-0.22**	0.02	-0.09	**0.23**	**-0.22**	**-0.28**	**-0.46**	**-0.29**	**1.00**																				
3a	0.06	**-0.18**	**-0.16**	**0.17**	0.09	**0.63**	-0.08	-0.14	-0.03	**-0.16**	**1.00**																			
3b	-0.13	**0.20**	-0.03	-0.04	-0.03	**-0.21**	0.05	0.09	0.04	-0.03	**-0.37**	**1.00**																		
3c	0.08	0.01	-0.03	-0.04	0.00	-0.12	-0.05	0.09	0.04	-0.01	-0.14	**-0.42**	**1.00**																	
3d	0.10	-0.06	0.13	-0.11	-0.02	-0.13	-0.02	-0.02	-0.03	0.13	-0.15	**-0.45**	**-0.16**	**1.00**																
3e	-0.06	-0.10	0.11	0.07	-0.02	-0.01	0.08	-0.09	-0.06	0.08	-0.10	**-0.31**	-0.11	-0.12	**1.00**															
4a	0.02	-0.08	-0.15	**0.19**	0.00	**0.52**	0.10	-0.14	-0.03	**-0.24**	**0.52**	-0.08	-0.13	-0.14	-0.10	**1.00**														
4b	0.09	-0.06	0.08	-0.10	0.02	-0.06	-0.08	-0.03	-0.05	**0.16**	-0.04	**-0.18**	0.14	0.06	0.12	**-0.18**	**1.00**													
4c	0.07	**-0.22**	0.05	0.00	0.13	-0.07	0.09	-0.10	-0.05	0.11	-0.11	0.05	-0.03	0.08	-0.05	**-0.22**	**-0.35**	**1.00**												
4d	0.02	**-0.20**	0.05	0.14	-0.01	-0.09	0.05	-0.09	0.08	0.05	-0.06	0.02	-0.04	-0.02	0.10	**-0.16**	**-0.24**	**-0.31**	**1.00**											
4e	**-0.21**	**0.58**	-0.06	**-0.17**	**-0.16**	**-0.16**	-0.15	**0.33**	0.05	**-0.16**	**-0.17**	**0.17**	0.03	-0.04	-0.09	**-0.17**	**-0.26**	**-0.33**	**-0.23**	**1.00**										
5a	0.02	-0.14	0.01	0.00	0.13	0.00	-0.03	-0.12	0.03	0.12	0.06	0.01	-0.10	-0.04	0.10	-0.01	0.09	0.03	-0.06	-0.07	**1.00**									
5b	0.00	**-0.26**	0.05	**0.16**	0.04	-0.08	**0.16**	-0.05	-0.03	0.00	-0.01	-0.05	0.03	0.04	0.00	-0.05	-0.08	0.12	**0.23**	**-0.24**	-0.15	**1.00**								
5c	**0.25**	**-0.16**	0.01	-0.11	0.06	-0.15	-0.04	-0.03	-0.10	**0.22**	-0.09	-0.09	0.12	0.08	0.02	**-0.16**	**0.29**	0.00	0.07	**-0.24**	**-0.16**	**-0.34**	**1.00**							
5d	**-0.17**	**0.65**	-0.11	**-0.20**	**-0.20**	**-0.18**	-0.14	**0.39**	0.08	**-0.23**	**-0.20**	**0.23**	-0.02	-0.08	-0.06	-0.10	**-0.17**	**-0.26**	**-0.19**	**0.73**	**-0.15**	**-0.32**	**-0.35**	**1.00**						
5e	-0.10	**-0.19**	0.02	**0.20**	0.05	**0.49**	0.07	**-0.29**	0.05	-0.10	**0.32**	-0.11	-0.08	0.00	-0.07	**0.39**	**-0.15**	0.13	-0.07	**-0.22**	-0.12	**-0.24**	**-0.27**	**-0.25**	**1.00**					
6a	**0.16**	-0.11	-0.12	-0.06	0.15	0.01	0.05	-0.06	-0.09	0.08	0.06	0.03	0.01	-0.06	-0.07	-0.02	-0.01	0.08	0.02	-0.09	0.12	**0.16**	0.06	-0.15	-0.15	**1.00**				
6b	-0.11	**0.25**	-0.07	0.02	-0.12	-0.06	-0.07	**0.20**	-0.05	-0.07	-0.02	0.12	0.04	-0.10	-0.12	0.08	**-0.21**	-0.06	0.02	**0.20**	-0.05	-0.08	-0.09	**0.25**	-0.05	**-0.44**	**1.00**			
6c	**-0.18**	-0.14	**0.31**	0.12	-0.11	-0.07	-0.02	0.02	0.02	0.03	-0.09	0.06	-0.07	0.01	0.07	-0.09	0.11	-0.06	**0.16**	-0.13	0.02	**0.16**	-0.03	-0.12	-0.05	**-0.25**	**-0.31**	**1.00**		
6d	0.07	-0.03	0.01	-0.03	0.00	0.03	-0.01	**-0.22**	0.14	0.10	0.01	**-0.24**	0.04	**0.25**	0.05	-0.11	0.11	0.03	**-0.16**	0.08	-0.01	-0.14	0.06	0.08	0.01	**-0.20**	**-0.25**	-0.14	**1.00**	
6e	0.09	-0.07	-0.07	-0.03	0.10	0.13	0.07	-0.05	0.05	-0.11	0.04	-0.08	-0.04	-0.01	**0.16**	0.11	0.11	0.02	-0.08	-0.14	-0.10	-0.13	0.05	-0.13	**0.32**	**-0.23**	**-0.28**	**-0.16**	-0.13	**1.00**

Sig. levels for N=166
0.1523 at 5% level two tailed – **bold font**
0.1994 at 1% level two tailed – **bold and underlined font**

Table O.6.
Correlations between answer choices; All Middle schools; WALL Context; N=68

	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e	6a	6b	6c	6d	6e
1a	**1.00**																													
1b	-0.17	**1.00**																												
1c	**-0.38**	-0.14	**1.00**																											
1d	**-0.29**	-0.10	-0.23	**1.00**																										
1e	**-0.38**	-0.14	**-0.31**	-0.23	**1.00**																									
2a	/0	/0	/0	/0	/0	**1.00**																								
2b	0.04	-0.09	0.12	-0.15	0.01	/0	**1.00**																							
2c	-0.06	-0.13	-0.13	0.18	0.12	/0	-0.19	**1.00**																						
2d	**-0.26**	**0.37**	0.23	-0.10	-0.07	/0	**-0.24**	**-0.36**	**1.00**																					
2e	**0.28**	-0.18	-0.19	0.04	-0.05	/0	**-0.27**	**-0.39**	**-0.49**	**1.00**																				
3a	0.08	-0.08	-0.07	-0.14	0.15	/0	-0.12	0.05	-0.12	0.15	**1.00**																			
3b	-0.19	**0.37**	0.00	0.08	-0.07	/0	-0.05	-0.13	**0.45**	**-0.29**	-0.23	**1.00**																		
3c	0.09	-0.13	-0.04	0.08	-0.04	/0	0.14	-0.03	-0.05	-0.02	-0.18	**-0.36**	**1.00**																	
3d	0.06	-0.19	0.08	-0.06	0.01	/0	0.01	0.11	**-0.31**	0.20	**-0.26**	**-0.51**	**-0.41**	**1.00**																
3e	/0	/0	/0	/0	/0	/0	/0	/0	/0	/0	/0	/0	/0	/0	**1.00**															
4a	**0.25**	-0.04	-0.10	-0.07	-0.10	/0	-0.06	-0.09	-0.12	0.24	**0.51**	-0.12	-0.09	-0.13	/0	**1.00**														
4b	0.19	-0.17	0.06	-0.20	-0.01	/0	0.04	-0.14	0.22	-0.12	-0.03	0.01	-0.06	0.06	/0	-0.12	**1.00**													
4c	0.04	0.11	-0.05	0.01	-0.05	/0	0.16	-0.03	**-0.29**	0.20	-0.22	0.06	-0.03	0.11	/0	-0.11	**-0.45**	**1.00**												
4d	-0.13	-0.08	-0.07	**0.27**	0.04	/0	-0.12	0.17	-0.02	-0.05	0.04	0.09	0.17	**-0.26**	/0	-0.06	-0.23	-0.22	**1.00**											
4e	**-0.25**	0.14	0.08	0.05	0.08	/0	-0.11	0.10	0.13	-0.14	0.03	-0.09	0.02	0.05	/0	-0.10	**-0.40**	**-0.37**	-0.20	**1.00**										
5a	**0.36**	-0.06	-0.14	-0.10	-0.14	/0	-0.09	-0.13	-0.17	**0.34**	**0.53**	-0.17	0.02	-0.19	/0	**0.70**	-0.04	-0.16	-0.08	0.00	**1.00**									
5b	0.01	-0.15	**-0.25**	**0.41**	-0.02	/0	0.19	**0.24**	**-0.33**	-0.02	-0.20	-0.11	0.00	0.23	/0	-0.10	**-0.34**	**0.42**	0.02	-0.04	-0.15	**1.00**								
5c	0.12	-0.23	0.12	**-0.30**	0.12	/0	0.03	0.01	0.09	-0.12	0.08	0.09	0.01	-0.15	/0	-0.16	**0.57**	**-0.27**	0.08	**-0.32**	-0.23	**-0.55**	**1.00**							
5d	**-0.35**	**0.49**	0.23	-0.01	-0.11	/0	-0.19	-0.18	**0.37**	-0.07	-0.17	0.13	-0.01	-0.01	/0	-0.09	**-0.27**	-0.01	-0.05	**0.38**	-0.13	**-0.31**	**-0.47**	**1.00**						
5e	-0.08	-0.03	-0.07	-0.05	0.22	/0	-0.04	-0.06	-0.08	0.17	-0.04	-0.08	-0.06	0.16	/0	-0.02	-0.08	-0.08	-0.04	0.21	-0.03	-0.07	-0.11	-0.06	**1.00**					
6a	**0.33**	**-0.24**	0.09	-0.07	**-0.26**	/0	0.10	-0.09	-0.01	0.02	-0.04	-0.14	-0.23	**0.36**	/0	0.18	**0.27**	0.02	-0.23	-0.22	0.01	0.15	0.12	**-0.28**	-0.12	**1.00**				
6b	**-0.24**	**0.39**	0.02	-0.09	0.10	/0	-0.24	0.20	0.13	-0.14	0.21	0.06	0.12	**-0.29**	/0	-0.11	**-0.31**	0.01	0.10	**0.30**	-0.02	-0.17	-0.07	**0.31**	-0.08	**-0.63**	**1.00**			
6c	-0.15	-0.09	-0.09	0.11	0.23	/0	**0.29**	-0.19	**-0.24**	0.21	-0.12	0.05	0.03	0.01	/0	-0.06	-0.15	0.16	0.03	0.00	-0.09	0.09	-0.15	0.04	**0.33**	**-0.35**	-0.24	**1.00**		
6d	-0.04	-0.06	-0.14	**0.25**	0.01	/0	-0.09	0.02	0.10	-0.05	-0.08	0.10	0.17	-0.19	/0	-0.04	0.09	-0.16	0.12	0.00	0.20	-0.01	0.02	-0.13	-0.03	**-0.24**	-0.16	-0.09	**1.00**	
6e	0.00	-0.05	0.05	-0.09	0.05	/0	-0.08	0.06	0.01	-0.01	-0.07	0.01	0.06	-0.02	/0	-0.04	0.16	-0.14	0.16	-0.12	-0.05	-0.13	0.09	0.07	-0.03	-0.21	-0.14	-0.08	-0.05	**1.00**

Sig. levels for N=68
0.236 at 5% level two tailed – **bold font**
0.307 at 1% level two tailed – **bold and underlined font**

APPENDIX U
USING PROGRAMS FOR DATA ANALYSIS AND TEMPLATES FOR DATA REPRESENTATION

1 Templates for data entry and scoring

In order to be analyzed, students' results obtained in the test should be entered so that the answers of each student are in tabular form - in the same row and in six adjacent columns (i.e. four columns for four question tests). The provided template for data entry is in Microsoft Excel® format and it automatically performs a simple statistical analysis of data. The file is on the CD in folder No. 2.

The same folder also contains a template that scores the results of each student in terms of the correct answers he or she gave. Finally, this folder contains a template that converts the results that are obtained in a numerical format (so that no 1 corresponds to answer "a," 2 to "b" and so on up to 6) into a letter format that analysis programs recognize. This numerical format is obtained, for example, if WebAssign® is used (www.webassign.com).

2 Programs for model analysis of results

There is a program that analyzes test results in terms of students' mental models that corresponds to each of the test versions. These programs are written in Microsoft Excel® and can be found on the CD in folder no 3. The students' answers can be analyzed if they are entered in the format described in section 1 of this appendix. Data have to be entered in the worksheet "Analysis" in the space provided for that (columns B-G, row 2 and onwards). The results of the data analysis then appear in other sheets of the same Excel file in numerical and graphical format as described in Appendix L. The details of using these programs in real time with a PRS system are described in Appendix U-1.

3 Programs for statistical analysis of results

Folder No. 4 on the CD contains four programs (MS Excel) that enable the user to perform different statistical analyses of data simply by cutting the results and pasting them into the appropriate columns. These programs either calculate the desired values automatically after the data is entered or they require a few simple steps on the user's part in order for the desired calculation to be performed. Programs are given for calculation of:

1. Correlations between the answers. After data is entered in columns B-G, the program translates the data into "1" and "0" pattern in columns AJ-BM. The user then needs to perform a correlation analysis of this data using the standard Excel function. Obtained correlations can be pasted into a Word document using the template provided in folder 5 on the CD.
2. Significant levels of correlation coefficients. If the exact number of degrees of freedom needed is not given in the table, this program linearly extrapolates table values for any number between 1 and 1000. The desired number has to be entered in columns E-F and the desired correlation at levels 1 and 5% two tailed appears

in column K. One needs to enter a number in the column F so that its sum with the number in column E makes the desired number of degrees of freedom.

3. The final program in this statistical package calculates whether there is a significant difference between the students' responses if different versions of the test are administered. Users need to enter the results of one of the test versions in columns B-G and another in columns K-P. The results are automatically displayed in columns AC-AJ on the right side of the data entry (to conveniently place results, intermediate calculations in columns S-AB are hidden and if necessary the user can easily unhide them).

4 Templates for presentation of findings

These templates are in folder 5 on the CD and are given to make it easier for the user to present the findings of his or her class. In addition the Excel programs automatically perform some useful analysis. Because programs for analysis are large files, once the results are calculated and displayed in the sheet called "PP Data" (PP stands for PowerPoint), they can be entered into Excel templates provided in folder 5 on the CD. If different contexts were used, this Excel file will automatically calculate the weighted average results for the whole class so that both contexts are included. The results can then be entered into provided Power Point Presentation templates on corresponding slides.

APPENDIX U-1
USING THE TEST WITH THE PRS CLASS RESPONSE SYSTEM

MS Excel files needed to analyze data in real time are on the dissertation CD in folder 3. Folder “Final Programs” (within folder 3) contains three folders called “PRS Hot Link.” Each of them is associated with a number (N) which denotes the maximum number of students that the program can analyze (150, 250 and 500 students). Files were separated this way because file size rapidly increases with the number of students a program can handle and it is likely that many of the classrooms where this test can potentially be used will not have more than 150 students.

However, if necessary, it is easy to increase the number of students that the program can handle by inserting new rows and copying formulas in them. If a user has a problem with this, he or she can visit the websites in Appendix W and look for updated and expanded programs, or contact the author.

If, for example, the desired number of students is less than 150, the user would select the folder “PRS HOT LINK N=150.” Within that folder, the user will find two folders - each corresponding to one of the two 4-question test versions (both related to air context. These are: “HOT LINK Q1234” and “HOT LINK Q2356”.

These folders contain two files. One is called “sound1” (for Q1234 test version) and the other is “sound2” (for Q2356 version). This is the file in which data collected from students are saved when a session is over.

Another file is the analysis program which performs all of the necessary operations and displays results in relevant charts. If, for example, test version Q1234 is used the files in folder “HOT LINK Q1234” will be needed.

The resulting file associated with it is called “sound1” and the analysis program (for N≤150) is “AIR Analysis Program 9.2 Q1234 Hot Link N=150” and it is linked to “sound1.” This link enables data in the “sound1” file to be analyzed and displayed in relevant charts of the analysis program as soon as the session is closed,. However, in order for the file to be saved it can not be open during the session. And in order for the analysis program to analyze new data, “sound1” has to be opened once the session is closed.

The PRS by default saves sessions into a folder which is (again by default) placed in C:/Program files/PRS/Session. The user should copy both files from the folder “HOT LINK Q1234” into this “Session” folder (C:/Program files/PRS/Session).

When the PRS is started, the following information is needed:

- Under the “Mode” drop down menu, select “Multiple choice.”
- Under the “Session” drop down menu, select “5 choices.”
- Under the “Session” drop down menu, select the number of chances according to your preference.

The next step is to start a new session. You will be asked:

“Do you want to save the session when finished? – Click Yes

You will be asked to choose a name and folder of the file to be saved and “Session” folder will be offered. The PRS session is saved in .cvs format so sound1.cvs file will be visible. Overwrite the “sound1” file by naming the new session “sound1.”

The analysis program can be opened in advance to save time later. The “sound1” file, however, has to be closed until the session is over and then should be opened in order for the data to be analyzed. Once “sound1” is opened, the analysis program will automatically analyze its content and display the results.

APPENDIX V
SUGGESTED INSTRUCTIONAL APPROACH

The instructional approach that we suggest is based on a combination of the effective research-based methodologies all of which to a good extent fit the description of "guided discovery" methods. In essence, the suggested instruction format is a version of modeling instruction,{Physics Education Group at Arizona State University, 2000 #305; Hestenes, 1996 #244} which is an adaptation of the learning cycle. The suggested approach contains a problem formatted according to the Context rich problem method.(University of Minnesota Physics Education Research Group, 1995) Socratic dialog (Hake, 1992)is emphasized as well as aspects of Peer instruction (Mazur, 1997)and SCALE-UP methodology.(Beichner, Saul, Allain, Deardorff, & Abbott, 2000) The proposed lecture follows the following format:

1. Investigation of phenomena (context rich problem)
    a. the designing of experiments (kinesthetic involvement)
    b. the use of evidence to back up conclusions (presentation)
2. Explanation of phenomena (Socratic dialogue, Peer instruction)
3. Application of created understanding

1 Investigation phase

This "lesson" is proposed while keeping in mind a studio-like classroom setting in which 20-40 students work in groups of three or four. The same lesson proposed below can be used with very few changes with a larger number of students if a setting is similar to the SCALE-UP arrangement.(Beichner et al., 2000)

The Modeling Instruction method (Physics Education Group at Arizona State University, 2000)has two distinct phases: Model development and model deployment. The problem that is given in this case is: Make a model for sound propagation in the air. This question has many features of the "Context rich problem" (University of Minnesota Physics Education Research Group, 1995)

The beginning phase of the lesson that we propose would be similar to the exploration phase of the learning cycle approach with extensive kinesthetic involvement. Students would have an opportunity to play with various sound producing devices while trying to construct the model. To facilitate meaningful modeling (creation and/or refinement of the model) the following questions will be provided as guidelines:

1. Is any motion needed in order for sound to propagate (that does not exist when sound does not propagate)?
2. If so, motion of what? What is it that moves for this purpose?
3. What kind of motion? How it (whatever moves) moves?
4. Is there anything that obstructs the motion?
5. How is this motion related to sound?

When students in all of the groups are done with this activity, a representative of each group would explain their model. We can assume that proposed models will fall into one of the four categories described pictorially with great certainty. This was the case with the middle school sample of 99 children described in section 5.5. The teacher's role is to summarize proposed models as students present them. The teacher has to make sure that students are satisfied with the way their models have been summarized and presented to the class as a whole. Pictorial representations of the models given in Appendix I can be very helpful for this representation. Research indicates that not only younger students like pictorial stories but high school students do too.(Spicer, 2003)

As a valuable help in elicitation of students' mental models, the teacher can create the following table and fill it out as students talk. The table lists all things involved in sound propagation that students propose, the nature of motion of those things and the relation of these dynamics to sound.

Table V.1. Possible components of mental models of sound propagation

Object(s) - What moves	**Motion – how involved objects move**	**How is this motion related to sound**
Possibilities		
- Air particles - Sound particles	- Some move (sound particles) some do not (air particles) - In direction of prop. - Transversal - Longitudinal - Any combination of the above three	- Is sound - Carries the sound - Obstructs the sound - Causes the sound in the listener's ear

Table V.2. Example of set of components of mental models of sound propagation

Object(s) - What moves	**Motion - how involved objects move**	**How is this motion related to sound**
Air particles	From the speaker to the listener	It causes sound when it kicks the listener's ear.

After students present their models, the teacher will make sure all students understand all proposed models. After the models have been elicited and mapped out, incorrect models will be challenged through experiments. Table V.1 can later be used again to help address proposed mental models, i.e. to eliminate incorrect ones. The table can be helpful because it allows the teacher to discuss and eliminate incorrect models by eliminating some of their particular aspects. This can be done in two different ways (described below in sections 1.1 and 1.2) and the optimal way depends primarily on how much time a teacher has, but also on how students perform in the exercise.

1.1 Idealized scenario and its problems

If time allows, the following exercise would be very beneficial for the development of scientific inquiry skills and epistemologically favorable beliefs. The task for students would be to think of experiments which could show that their model is correct and/or that others are incorrect. After that the teacher would call for another round of presentations.

In an idealistic (but unrealistic) scenario some students would have a Wave Model and they will propose some experiment that can be explained only in terms of the Wave Model. Students who come up with other models ideally will propose experiments that will support only their model, so different experiments will eliminate all incorrect models. The teacher will perform the proposed experiments by starting with experiments that do not make a distinction between models (that could be explained by different models) and later proceed with "degeneracy breaking" experiments. This sequence is crucial for development of students' self-confidence (all students will be at least partially right). Also, becoming familiar with this procedure is crucial for students' understanding of the nature of the scientific enterprise and according to Shamos (Shamos, c1995)for meaningful scientific literacy.

A few problems might be associated with this idealized scenario:

- Time is always an issue in instruction and in the above scenario we propose two modeling cycles (each of which may take a substantial amount of time).
- Students rarely use the Wave Model even after instruction and it might happen that nobody proposes this model before the instruction.
- Even if somebody does, it might happen that students do not propose a "model degeneracy breaking" experiment.
- The teacher would need to be very resourceful in terms of the equipment to actually perform all experiments proposed this way.

1.2 More realistic scenario

Because of the mentioned problems, we propose an alternative scenario keeping in mind the benefits of the ideal one and striving toward them. After the modeling cycle where students propose their models, the teacher can announce that s/he will perform several experiments related to sound.

1. Before each experiment the teacher will ask students to consider a familiar situation that deals with the same kind of phenomena that the experiment deals with.
2. After this request and before the experiment, the teacher will ask students to predict the outcome of the experiment based on their model. This is a real hypothesis testing and a simulation of scientific research. It is an experience of many teachers that this can be used to create positive tension in the classroom before the experiment.
3. After each experiment, each group of the students will determine if their model can explain the result.
4. If not, they will be asked to modify their model or adopt another one so the improved model can explain the experiment.

If the teacher decides to use an elimination procedure related to items in the table, he/she can ask students if the demonstrated experiment or analyzed situation eliminates or reinforces any of the items in the table with things listed during students' presentations. This way, incorrect items (and corresponding models and sub-models) will be eliminated.

1.2.1 Notes related to proposed lesson

Before continuing with the proposed sequence of the experiments, several points should be mentioned.

1.2.1.1 Wave Model

It is okay if no one proposes the Wave Model during instruction. Eventually, the experiments will show that the proposed models are not good enough and that an additional one is needed. Students can then go once again to the original set of questions and this time, based on the experiments they saw, their task will be to answer the questions so that the model can explain the observed experiments. This is another activity that is very beneficial for students' epistemological beliefs and understanding of science.

If students still do not come up with a wave or a wave-like model, the teacher can guide them to simply explore possibilities according to Table V.1 which s/he will have drawn based on students' original models. At this point the teacher can, in agreement with the students, disregard things in the table that the experiments proved wrong. Also, if the correct answer is missing in any of the three columns, the teacher can prompt students to fill the "remaining possibilities" – again based on logic and experiment.

1.2.1.2 Everyday situations and experiments

Some sound experiments and everyday situations can be nicely explained not only with a Wave Model but also with a particle model (e.g. a reflection of sound). Therefore, while probing proposed models in the phase when we want to show (partial) validity of all proposed models of everyday situations can serve the purpose well.

1.2.1.3 Selection of experiments

Experiments proposed in the "lesson" below differ in their level of sophistication. Different levels of complexity have different (dis)advantages. Simple experiments require materials that can be easily found in our daily surroundings. Those experiments will more than likely get across the idea that the things we are dealing with in the "lecture" are our everyday reality. More complex experiments, or ways of data collection, have other advantages (precision, sophistication) so they can also be used when simple experiments do not have good enough "resolution," i.e. when their outcome can be explained in many different (incorrect ways). High tech experiments on the other hand may draw students' attention to the wrong things so experiments with different levels of complexity should be balanced.

1.2.1.4 Transfer

Modern theories of learning and transfer recognize the importance of bridging the new material with old and familiar situations / concepts. This is the idea behind using everyday situations in questions before experiments or as "ponderables" (as they are called in SCALE UP methodology). That way, students will realize that the lesson is related to something that is around them all the time. After considering the situation, an experiment will be performed that demonstrates the corresponding principle (involved in the proposed everyday situation).

1.2.2 Sequence of experiments

I propose to start with a discussion about proposed models of sound propagation by using the phenomena of reflection of sound. That is because, most likely, all models that students may propose will be good enough to explain reflection of sound. The benefit of this strategy is the development of a student's self-confidence and understanding of the nature of the scientific enterprise.

1.2.2.1 Reflection

The teacher will ask students to consider if their models can explain the following situations:

- Questions:
  - Echo and reflection of sound?
  - Why we hear better when we shape our hand around the ear like a "big ear."

Most likely, the students will find their models plausible in explaining these situations. The related experiments (reflection of sound from the concave surface) will also, most likely, have the outcome consistent with the students' prediction. Thus, reflection is not "capable" of eliminating any of the items in the table.

- Experiment: Reflection of sound from the concave surface.

This experiment is the audio analog of experiment with light in which rays are focused by a concave mirror to a point. The experiment is performed so that two concave parabolic reflectors are used. A "beam" of sound is produced using a speaker at the focal point of one reflector and it is detected by a microphone placed at the focus of a second reflector.

1.2.2.2 Transmission

After all supportive reflection, the author proposes an investigation of the transmission of sound.

- Questions:
  - Why do we hear on the other side of the closed door?
  - Can we hear through the wall? Explain why?

Based on the author's experience and research, particle-like models can be adapted so they are able to explain transmission, but this will require some adjustments to the model.

- Experiment: Vacuum with a bell inside.

In this experiment there are no air particles under the bell, so we can verify if they are needed for sound propagation. The experiment demonstrates that when an air pump sucks out the air, sound can not be heard although the clapper is striking the bell. This shows that sound particles (or sound entities) either do not exist or, if they do exist, they need air to move. Therefore, this experiment is capable of eliminating the Independent Entity Model but not others. It shows that particles of the medium are needed so we still need to consider the Dependent entity, Ear-born, Intrinsic and Wave Models.

1.2.2.3 Interference

We can eliminate the Dependent Entity Model by using phenomenon of interference. When sound is produced in two sources, the Dependent Entity Model allows either for an unchanged level of loudness of received sound or for a constructive interference (increased loudness). But, it can not explain destructive interference unless students claim that sound entities can annihilate one another. If they do, then constructive interference is a problem.

- Experiment: Interference of sound coming from the two loudspeakers.

Discussion after the experiment: This result, in addition to the one with the vacuum, shows that there are no sound entities (particles). The only thing that remains possibly involved in the sound propagation is air particles. Therefore, the remaining dilemma is between Intrinsic Propagating Air and the Wave Model. At this point a teacher can ask: If air particles are all there (no sound entities in the air) do they move differently when there is sound or when there is not? Most likely the answer will be "Yes." This opens the question about how to find out how they move when sound propagates.

1.2.2.4 Experiment with candle flame

The question of air dynamics can be resolved through an experiment with a loudspeaker with a candle flame in front of it. With appropriate low frequency, a candle flame will oscillate back and forth in front of the loudspeaker and demonstrate that air particles vibrate longitudinally and not transversally.

At this point, according to Table V.1., it was demonstrated that objects involved in sound propagation are air particles and they move longitudinally. The question is still how this motion is related to sound. The elimination of the sound particles eliminated the options that this motion of the air carries the sound particles (entities) or obstructs them. The remaining options are that this motion a) is sound or b) causes the sound in the listener's ear.

1.2.2.5 Ear-born discussion (optional):

A discussion on ear-born sound is necessary in case both options are suggested by students (motion is sound or motion causes the sound in the ear) or in the case that only the ear-born option is mentioned. In either of these cases the discussion proposed below may help to get the idea of sound as an "intrinsic" wave across.

We all know from our experience that there is a sound that we perceive by ear and interpret in our brain. We say we hear the sound. And from these experiments we see that there is something that causes this perception. Is the sound our perception or is the sound what causes this perception? Or is it both? To a good extent this is a philosophical question because it is primarily a consensus on the definition of sound that defines the answer.

The teacher can guide the discussion --- the purpose of which is to at least achieve agreement that sound is not *exclusively* what we hear. Also, that what we refer to as a sound (that we hear) and the mechanism of the sound propagation are two different things. In physics, the longitudinal mechanical wave in the medium is called sound. If this is understood, it is OK to continue using the term sound for what we hear while keeping in mind these issues in terminology.

The teacher can open some of these issues for discussion:

- Does sound exist in a forest when nobody is there and a tree falls?
  With the help of this question we may settle on a definition: Sound is independent of the observer. If he was there – the observer would register it. Since he was not there, he did not. Sound is what was going on due to the tree falling and what the observer would register IF he was there.
- Would a recorder record that sound if it was left there? Yes. So there was something independent from the observer.

Through discussion based on these questions students would realize the issue of the definition and the definition of sound in physics. Also, they will understand the advantage of the physics definition as one that enables scientists to be more objective.

Along these lines, another question could be raised: Are our chances to be objective better if we depend on what the observer hears or what can be registered with the instruments? If two recordings of sound are made by two recorders and they are then compared, sound is normally very similar, if not identical. However, two people may hear the produced sound very differently. (Especially if their age difference is large because hearing ability diminishes with age).

2 Concept introduction phase

At the end of these discussions the teacher will summarize and further explain the Wave Model.

3 Application phase

After the concept introduction phase, the teacher will continue with a new set of experiments, again in prediction-explanation mode. But this time s/he will expect more accurate responses, which will be based on the Wave Model. The correct model will be refined and hopefully "nailed down" this way. For this purpose new experiments can be used as well as everyday situations or the same experiments that were analyzed earlier, but this time from the "wave perspective."

In the new set, the author suggests the following experiments / situations.

- Diffraction of Sound: Bending of Sound by an Obstacle
  - Why we hear around the corner?
- Doppler Effect: Frequency Shift of Moving Sound Source
  - What happens when an ambulance siren approaches / leaves the listener?
- Interference revisited:
  - Sound Divided into Two Paths of Differing Length
  - Beat Phenomena
- Standing Sound Waves in Air Columns
- Sound propagation in other mediums such as a wall, steel, water…
  - Similarities and differences when propagation through these mediums is compared to propagation through air.

Conclusion

The basic idea of the proposed instruction format is to elicit students' models of sound propagation and then to eliminate the incorrect ones through demonstrations of appropriate experiments and Socratic dialog. Disequilibrium inducing experiments are:

- Reflection – supports all models
- Transmission through the wall – causes dissonance and revisions of models
- Vacuum bell – eliminates Independent Entity Model
- Interference – eliminates dependent entity and propagating air models
- Candle flame and speaker – shows dynamics of the particles of the medium
- Discussion on Ear-born sound

Literature:

APPENDIX W
WEB ADDRESSES FOR DOWNLOADS AND UPDATES

Downloads and updates related to this dissertation can be found at the following sites:

KSU PERG web page
http://web.phys.ksu.edu/role/sound/

or

Author's web page
www.hrepic.com

These web pages will keep current files related to tests, programs for data analysis, programs for representation of results and information related to the test usage.

The tests and related programs are free for use by teachers in their own educational setting.

In the interest of further research, the author would greatly appreciate the test users notifying him if they use the test. Even more importantly, sharing of the obtained results with the author will be much appreciated. The author's current e-mail will be available at www.hrepic.com.

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