THREE-TIER DIAGNOSTIC INSTRUMENT FOR INVESTIGATING ALTERNATIVE CONCEPTIONS

by

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ABSTRACT
This paper reports on the findings of a study which aimed to develop and apply a three-tier diagnostic instrument, called the Wave Diagnostic Instrument (WADI), to investigate the alternative conceptions (ACs) held by upper secondary students in Singapore in relation to the nature and propagation of some common wave phenomena (e.g., sound and light). The results obtained indicate that the students have considerable difficulties in understanding the principles related to these topics. The students were also found to be generally confident in the correctness of their responses, although their confidence levels varied across test items. Some strong alternative conceptions were found, which include the notions that the speed of sound increases with the density of the medium, and that sound cannot be refracted and propagate without air. It was found that a three-tier test is useful not only in identifying ACs, but also in knowing the strengths of ACs identified. They can be used to segregate mistakes due to lack of knowledge and guessing from mistakes that arise from flawed understanding of concepts.

Keywords**:** alternative conceptions, waves, three-tier diagnostic tests

Strand**:** Innovative Assessment

INTRODUCTION
The pervasiveness of the constructivist theory, which was first introduced in the 1920s by Piaget and given a further boost by Ausubel in the 1960s, along with the growing body of literature regarding conceptual change theory of learning in education have encouraged many researchers towards investigations of students' existing ideas. Students' conceptions about various topics in science that differ from established scientific knowledge, commonly termed as alternative conceptions (ACs), have been the focus of myriad studies. In investigating ACs, the use of two-tier multiple-choice (2TMC) tests (Treagust, 1988) has gained popularity. A 2TMC test comprises the *content* tier, which evaluates the descriptive knowledge of respondents; and the *reason tier*, which evaluates the "explanatory knowledge" or the "mental models" of respondents (Tsai & Chou, 2002, p. 158). One fundamental limitation of a 2TMC test, which also applies to the family of multiple-choice tests, is that it cannot differentiate mistakes due to lack of knowledge from mistakes due to genuine alternative conceptions; and conversely, it cannot differentiate correct answers due to guessing and correct answers due to genuine understanding (Hasan, Bagayoko & Kelley, 1999; Klymkowsky et al., 2006).

The foregoing limitation of 2TMC tests can be addressed by introducing a third tier to 2TMC items-- the confidence rating, thereby forming a three-tier multiple-choice (3TMC) item. Confidence rating is a construct related to metacognition, which can indicate the strength of students' beliefs. There were only a few studies in science education that linked confidence rating with understanding concepts or principles (Hasan, Bagayoko & Kelley, 1999; Clement, Brown & Zietsman, 1989). After conducting a thorough review of the literature about ACs, only four studies were found that dealt with the application of a 3TMC test: three dissertations (Al-Rubayea, 1996; Franklin, 1992; Hill, 1997) and a conference paper (Kaaltakęi and Didi□, 2007). In all of these studies that featured a 3TMC test, none has involved the calculation of confidence variables, such as confidence discrimination and confidence bias, which have been formalized in psychological studies that focused on confidence rating. There is a need for more studies to investigate the potential of 3TMC tests in exploring students understanding; in particular, studies that include more comprehensive analysis of confidence ratings in relation to students' understanding of science concepts.

This study intended to supplement the scant literature that feature the association between students' conceptual understanding and confidence rating in science, particularly in relation to 3TMC tests. Its main goal was to develop and apply a 3TMC test about the nature and propagation of waves. The students' understanding of waves has not been given ample attention in the literature that focuses on ACs and conceptual change. For this paper, we limit our discussion on the properties and propagation of waves, specifically low-amplitude mechanical waves that propagate through an ideal medium—that is, linear, non-dispersive, non-dissipative and flexible

METHODOLOGY

The Wave Diagnostic Instrument (WADI) was developed based on the responses of upper secondary students (who were not involved in the main study) to open-ended questions about waves, individual interviews, observation of class lessons and review of existing relevant literature. The WADI, the list of propositional statements that guided its development, and related concept map, were content-validated by four university academics and four secondary school physics teachers. The test was found to be in good order by the evaluators. The evaluators' comments were used to modify the test. The WADI was then pilot-tested and subsequently revised to form the 14-item final version. The final WADI was found to have a Flesch-Kincaid readability level of 7.3, which suggests the test's suitability for the reading level of upper secondary students. The internal consistency of the test, as indicated by Cronbach alpha, is .65. All the WADI items were found to be positively discriminating (.17 to .62), with discriminating power determined by taking the difference between the proportion of students in the upper 27% and lower 27% who gave correct responses per item.

This paper presents the responses to WADI of 243 students in Secondary 3 and 4. The sample comprised 52% males and 48% females from six average government co-educational schools in Singapore. WADI was administered to the students after they have experienced at least six hours of formal instructions on the properties and nature of waves.

RESULTS AND DISCUSSION

The results of the study suggest students' difficulties in understanding waves. The students had low mean scores in relation to content, reason and the combination of the two (see Table 1). The students seem to have found it easier to respond correctly to the content tier than to the reason tier. Furthermore, the difficulty level of a particular tier of the test seems to be positively associated with the students' confidence. Higher mean scores and mean confidence seem to be associated with the content tier than the reason tier.

Although the students expressed difficulties in dealing with wave-related concepts, they were, on average, confident that their answers were correct (mean confidence=3.60). Overall, the participants were found to have a low mean confidence discrimination quotient (CDQ=0.11): that is, they tended to poorly discriminate between what they know and what they do not know. Nevertheless, the students appear to be generally more confident when they were giving responses that were actually correct (CFC=3.70) than when giving responses that were actually wrong (CFW=3.54).

The students were also found to be generally overconfident: that is, their mean confidence level is beyond what was warranted by the accuracy of their responses. The students' mean confidence bias (which is the difference between confidence of students recoded into a scale of 0 to 1 and the proportion of students who selected correct responses) was positive (.27). The overconfidence detected in the present sample is in harmony with the findings of other studies involving the confidence of students in taking varied types of tests, mostly done in the domain of psychology (Lundeberg, Fox, Brown & Elbedour, 1994; Renner & Renner, 2001).

Table 1 Scores and related confidence rating variables based on the administration of WADI to upper secondary students (N=243)

Variables	Mean	SD
Score [a] (content)	5.13	2.54
Score [a] (reason)	4.49	2.57
Score [a] (content and reason)	3.48	2.51
Confidence	3.60	0.70
Confidence when Correct (CFC)	3.70	1.07
Confidence when Wrong (CFW)	3.54	0.77
Confidence Discrimination Quotient (CDQ) [b]	0.11	0.71
Proportion Correct [c]	.25	.18
Confidence Recoded (0 to 1)	.52	.14
Confidence Bias [d]	.27	.18

[a] Maximum score is 14. [b] CDQ=(CFC– CFW)/ (Standard deviation of all confidence rating for the tier or item). [c] Proportion Correct= proportion of students who chose correct options. [d] Confidence bias (confidence rating recoded in a scale of 0 to 1– proportion correct).

For this paper, we focused only on student's responses to three WADI items: Q1, Q2 and Q3. These items assessed the students' conceptions about wave speed and density of medium, and about the behaviour and propagation of sound and light. The distribution of students' responses is shown below each question. The relevant propositional statements are interspersed in the discussion of the results per item.

Factors affecting wave speed

In a non-dispersive, linear and elastic medium (which are typical assumptions when dealing with mechanical waves in secondary physics), the longitudinal propagation speed of a mechanical wave (henceforth, wave speed) depends on the properties of the medium, namely, elastic and inertial properties. When the inertial property increases (e.g. mass per unit length), propagation speed is reduced because the particles of the medium has greater resistance to motion. But when the elastic property of the medium is increased, which means stronger interaction force between particles and greater resistance to compression or deformation, the propagation speed increases.

The large majority of the students (70.4%), in responding to Q1, believed in the scientifically correct view that sound travels faster in solids than in liquids and in gases, while 28.8% believed otherwise. Only 15.6% of the students chose the correct content-reason combination, B(b), which highlights the larger interaction force between the particles of solids than of liquids and then, of gases.

Q1: Arrange the three media, air, water, and steel, in order, starting from the medium through which sound propagates the slowest to the medium through which sound propagates the fastest.

Main answer:

	slowest	→	fastest
A.	steel	water	air
B.	air	water	steel **

Scientific reason for my answer:

A. The larger the space between the particles of a medium, the less is the obstruction for sound propagation. The space between particles is largest for gases and smallest for solids.
B. Sound travels faster in stiffer media, wherein the interaction forces between particles are stronger. These interaction forces are strongest in solid and weakest for gases. **
C. Sound travels faster in denser materials, wherein particles are closer together and the total mass of particles in a unit volume is greater. Solids have the greatest density, followed by liquids, and then gases.

Confidence Rating:

1	2	3	4	5	6
Just Guessing	Not very Confident	Not Confident	Confident	Very Confident	Absolutely Confident

Reason	(a)		(b)		(c)		No answer		Others		Total	
Answer	n	%	n	%	n	%	n	%	n	%	n	%
A	22	9.1	12	4.9	35	14.4	0	0	1	0.4	70	28.8
B	21	8.6	38	**15.6****	111.	45.7	0	0	1	0.4	171	70.4
No answer	0	0	1	0.4	0	0	1	0.4	0	0	2	0.8
Total	43	17.7	51	21.0	146	60.1	1	0.4	2	0.8	243	100

** Correct answer

Figure 1. Q1 with the number and percentage of students choosing each content-reason combination

For 45.7% of the students: "Sound travels faster in denser materials, wherein particles are closer together and the total mass of the particles in a unit volume is greater". These students could have based their response on the notion that the smaller the separation between the particles of the medium (which goes with greater medium density), the faster can they pass sound to the neighbouring particles. The AC, which is associated with options B(c), can be classified as a strong one as it was expressed with high confidence (4.57) by the students. Linder (1993), who conducted a study involving physics majors (N=14), also reported the existence of this AC.

In relation to Q1, the students were found to be generally confident both when they were choosing options which were actually correct (CFC=4.9) and when they were choosing options that were actually wrong (CFW=4.4) for Q1. Nevertheless, the former is slightly higher than the latter, thereby generating a positive CDQ.

Waves at the boundary of two media

All wave phenomena, including sound and light, can propagate from one medium to another. When waves are at the interface of two media, they tend to undergo changes in speed and direction. The change in direction of waves at the interface of two media is termed as refraction. About 31% of the students chose the correct options, B(d), in response to Q2. These students were found to be generally confident of the correctness of their response (CFC=3.8). However, the rest of the students who selected incorrect response-combinations were also generally confident that they have chosen the correct options (CFW=3.6). The sample indicated low confidence discriminating ability in relation to the concept of refraction (CDQ=0.2).

Q2: Which pairing of properties in the table below best describes light and sound?

Main answer:

Properties	**A**		**B ****		**C**	
	Light	sound	light	sound	light	sound
Can exhibit refraction	Yes	No	Yes	Yes	Yes	Yes
Can transport energy in a vacuum	Yes	No	Yes	No	Yes	Yes

Scientific reason for my answer:

A. Light propagates faster than sound. Sound is too slow to exhibit an observable change in direction and speed and to transport energy in a vacuum.
B. Light propagates in straight line and can propagate through a vacuum. Sound cannot do so.
C. Light can be seen and can propagate through a vacuum, but sound cannot.
D. Light and sound, being both waves, can undergo change in speed and direction as they propagate through different media. Light can propagate through vacuum but sound cannot. **
E. Light and sound, being both waves, can undergo change in speed and direction as they propagate through different media. Both waves can propagate with or without a medium.

Confidence Rating:	1	2	3	4	5	6
	Just Guessing	Not very Confident	Not Confident	Confident	Very Confident	Absolutely Confident

Reason	**(a)**		**(b)**		**(c)**		**(d)**		**(e)**		**Others**		**Total**	
Content	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
A	20	8.2	16	6.6	19	7.8	55	22.6	5	2.1	8	3.3	123	50.6
B	4	1.6	11	4.5	6	2.5	74	**30.5****	1	0.4	6	2.5	102	42.0
C	2	0.8	0	0	1	0.4	0	0	12	4.9	0	0	15	6.2
No answer	0	0	1	0.4	2	0.8	0	0	0	0	0	0	3	1.2
Total	26	10.7	28	11.5	28	11.5	129	53.1	18	7.4	14	5.9	243	100

**Correct answer

Figure 2. Q2 with the number and percentage of students choosing each content-reason combination

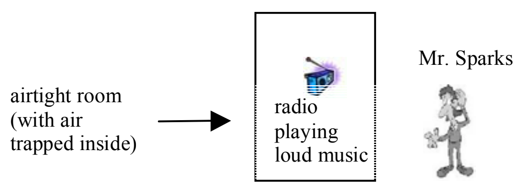
The AC that was detected in association with Q2 appears to be a consequence of the students' failure to develop a unified view of the behaviour of waves. Many students (50.6%) believed with confidence (3.67) that sound, unlike light, cannot exhibit refraction. In line with this belief, varied explanations were chosen by the respondents. Some students (7.8%) reasoned that sound, unlike light, is not visible. Others (8.2%) reasoned that sound is too slow to be refracted. For a few students (6.6%), it has something to do with sound being unable to travel in a vacuum and its perceived propagation in many directions, instead of the clear straight line that students see when they do experiments with light sources.

An additional insight that was revealed by the students' responses to Q2 is that they do not have much problem thinking that sound needs a medium to propagate through. This is suggested by the fact that only 6.2% of the respondents chose content option C, and just 7.4 chose reason option (e). The students' beliefs about the need for a medium for the propagation of sound were assessed using Q3.

Role of air in sound propagation

Sound is a mechanical wave that needs a medium to propagate through. It can travel not only in air or gases, but also through other media (namely, solids and liquids) and from one medium to another. Only 37% of the students expressed an awareness of this view. These students were, on average, confident of the correctness of their responses (CFC=3.8). However, those who chose incorrect response-combinations were even more confident (CFW=4.0). Thus, the CDQ of the students turned out to be negative for Q3.

Q3: The openings of an ordinary room are sealed so that no air from the room can come out. A radio is playing music loudly in the middle of the sealed room. If Mr. Sparks is standing about 50 cm away outside of the room, is he likely to hear the sound coming from the radio?



Main Answer:

A. No B. Yes **

Scientific reason for my answer:

A. Sound needs a medium for its transmission. If the air cannot move out of the room, there is no medium to transmit the sound outside the room.
B. Sound cannot pass through solid walls without small openings/gaps.
C. The wall reflects the sound, so it cannot go out.
D. Sound can be transmitted from one medium to another, e.g., from gas to solid. **
E. ____

Confidence Rating: 1 Just Guessing; 2 Not very Confident; 3 Not Confident; 4 Confident; 5 Very Confident; 6 Absolutely Confident

Reason	(a)		(b)		(c)		(d)		Others		Total	
Answer	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
A	115	47.3	10	4.1	10	4.1	0	0	2	0.8	137	56.4
B	4	1.6	1	0.4	2	0.8	91	**37.4****	7	2.9	105	43.2
No answer	0	0	0	0	1	0.40	0	0	0	0	1	0.4
Total	119	49.0	11	4.5	13	5.3	91	37.4	9	3.7	243	100

** Correct Answer

Figure 3. Q3 with the number and percentage of students choosing each content-reason combination

About half of the respondents chose response combination A(a) of Q3 (mean confidence=4.15) which suggests belief in the view that if air is trapped, along with its source, in a room; an outside receiver cannot hear the sound from the source, as the main medium, which is air, cannot reach the receiver. This view is, perhaps, associated with the notion that the particles of the medium, especially of a fluid one, travel together with the wave. Eshach and Schwartz (2006) also detected a similar view, based on the interview responses of five eighth grade students in Israel who were not exposed to any formal instruction on sound. In their study, the students were found to espouse the notion that sound is like an entity that can be locked up.

CONCLUSION

This paper shows that a three-tier test is a useful tool that can be used to assess students' conceptions of science topics, in particular, the assessment of the nature and strength of ACs in relation to the nature of waves and wave propagation. The three-tier test on waves, which was developed in this study, can be utilized by teachers in identifying aspects of the topic that require greater attention.

The strong ACs that we found include the view that sound can be trapped or locked up in a particular enclosure whenever air (or gases), which is viewed as the most important medium for sound propagation, is also trapped in this enclosure. Another strong AC is the notion that enhancing the density of the medium makes sound travel faster. Another significant AC, although relatively weaker, is the view that sound cannot be refracted.

These ACs may adversely influence the students' future learning, which utilizes understanding of waves. Teachers are encouraged to emphasize that sound, along with other waves, can be transmitted from one medium to another. Examples illustrating that sound, just like other types of waves, can also exhibit refraction (which is normally associated with light) can be cited to students to help them embrace a more unified view of waves. The principle that associates the speed of mechanical waves with the elastic and inertial properties of a medium is currently not included in the 'O' level Physics syllabus. We recommend that this principle be presented to students, at least conceptually, to minimize the development of strong ACs about the factors that influence the speed of waves. These ACs were found to be persistent, noting that they were also reported in relation to university students (Wittmann, Steinberg &Redish, 2003).

It was also found that the participating students were generally overconfident and had a low ability to discriminate between what they know and what they do not know. The ACs of these students would be difficult to modify. They are likely to allot less time and effort to learn about the topic. It is important to inform these students of the inaccuracies in their confidence judgment. We recommend that strategies, which may help the students to improve their ability to monitor their knowledge, be developed. We believe that if students can effectively monitor their knowledge, the occurrence of strong ACs can be minimized.

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