Assessment of problem solving activity on wave physics in secondary school

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Abstract. Italian secondary school students struggle with understanding wave-like phenomena. Many research-based materials are available on the topic, but their applicability is often limited by the constraints of actual school settings. We developed a set of conceptual problems on wave phenomena and tested them in classroom within a design-based research framework. We present the preliminary results of an on-going work that aims at providing teachers with high-quality versatile materials, along with testing our hypotheses on the learning processes.

1. Research questions and methodology
To promote a sound conceptual understanding of wave-like phenomena, we developed and tested problems on wave properties, superposition and interference, based on the operative principles drawn from our theoretical framework. Our main research questions are:

- Are our operative principles able to provide implications for teaching and learning?
- What naïve conceptions do students hold related to the topic of wave-like phenomena?
- Is the collective solution and discussion of our problems helpful in improving learning outcomes and problem-solving skills?

The design-based methodology appears to be well suited to the conditions and characteristics of our research [1-6]. Indeed, we are interested both in the production of instructional materials that teachers may routinely use in their classroom and in testing our domain-specific theoretical principles in a realistic context. The constraints and timing of the school settings make it convenient to adopt an iterative design, which includes the repeated implementation and a step-by-step improvement of classroom interventions, in close collaboration with teachers. Our epistemological paradigm is pragmatic: we aim at reaching useful conclusions that lead to practical implications for teaching.

To assess the impact of our activities on students’ learning outcomes, we devised two instruments: a multiple-choice questionnaire and a concept map. The questionnaire is used to compare the students’ performance before and after our classroom intervention. From the analysis of the concept maps built by the students, we can gain deeper insight into their knowledge organization and understanding of wave-like phenomena.

2. Design of the activities
The operative principles, that underlie the development of our activities, stem from a variety of disciplines and perspectives, notably from Ausubel’s theory of meaningful learning [7,8] and diSessa’s
theory of phenomenological primitives [9,10] but also from outlooks by cognitive neuroscience [11]. According to these principles:

- Learning must be rooted upon what the learner already knows. New concepts must be introduced starting from familiar topics or real life experiences, taking into account our “intuitive physics” [10].
- Learning must be integrated into the existing knowledge structure. The use of multiple representations and the confrontation of concepts across different contexts encourage the creation and strengthening of connections.
- Learning must be meaningful to the learner. Relevance of technological applications and implications for everyday life must be emphasized.
- Learning must be encouraged through positive feedback. Peer collaboration and class discussions enhance meta-learning and self-monitoring skills.

In accordance with these principles and with the available literature on problem solving, our activities should challenge conceptual understanding, focus on the qualitative analysis of the situation [12,13] require the use of multiple representations [14-16] and promote the reinforcement of meta-abilities through peer interaction [16-20] to help students strengthen their problem solving skills [21-23]. As a result, our problems integrate qualitative and quantitative aspects. They stem from real-life situations and require students to reflect upon familiar phenomena. The proposed activities place emphasis on the translation of words and formulas into drawings and graphs; they can be assigned either as individual or group work and then used to explore students’ ideas through a guided collective discussion.

As regards the contents, we used the available research literature on students’ reasoning about waves as a starting point to elicit and confront the most common difficulties. For example, the idea that the wave frequency affects its speed of propagation [24-27] or that sound waves are transverse waves [24-26, 28]. Other common misconceptions are that a particle perturbed by a sound wave moves away sinusoidally/is swept away/oscillates transversally [25, 27, 29] and that waves can collide, bounce, or lose energy when they meet [24, 27, 28, 30]. Students are often unable to draw the result of the superposition of two pulses [24, 27, 31] and believe that the interference pattern in Young double slit experiment is unchanged/dimmer/half-split if one slit is closed [32 – 34].

However, to the best of our knowledge, almost no reference to the concept of coherence appears in the literature. We report below an example of our problems:

Have you ever wondered how an acoustic guitar works? The answer lies in the principle of stationary waves. Indeed, guitar strings vibrate between two fixed points. When we play guitar, we do not produce a “pure” sound, i.e., characterized by a single frequency, but a sound that is composed of several harmonics.

a) Think about the quantities that characterize a wave. What is the effect of plucking the strings with “greater strength”?

b) Guitar strings have different thickness; moreover, three of them are usually made of nylon, while the other three are made of metal-covered nylon or simply metallic. Why?

c) What is the function of guitar frets? If you want to produce higher-pitched sounds, do you need to use frets that are nearer to or farther from the soundboard? Why? Use a drawing to help you answer.

d) A string of 60 cm length vibrates in its third harmonic with a period T=5x10⁻³ s. Calculate the speed of propagation of the wave and the frequency associated with its fifth harmonic.

To tune a guitar, the A key at 440 Hz is taken as reference. By comparing the A emitted by a tuner with the A note on our guitar, we can change the tension of the string until the two sounds have the same frequency. The A key is the fundamental harmonic of the second string.

e) If the A note on your guitar is initially at 432 Hz and your string is 60 cm long, do you need to increase or decrease the tension? By how much?

3. Implementation, data collection and analysis

3.1. Timing and structure of the activity
We implemented the activity during the school year 2016/2017. The first implementation occurred between February and March 2017 and involved a total of 110 high school students (age 17-18) from Liceo scientifico “Galileo Galilei” (Ancona, Italy), Istituto d’Istruzione Superiore “Francesco Filelfo” (Tolentino, Italy) and Istituto d’Istruzione Superiore “Leonardo da Vinci” (Civitanova Marche, Italy). The results of this first phase allowed us to slightly modify and improve the structure of the activity. Then the second implementation took place between April and June 2017, with the participation of 67 students (age 17-18) from Liceo scientifico “Medi” (Montegiorgio, Italy), Liceo scientifico “Volterra” (Fabriano, Italy) and Liceo scientifico “Cambi” (Falconara, Italy).

All students had already received traditional instruction on the topic between a few days and a month prior to our intervention. The activity took place in three two-hour sessions, both during regular classroom time and after school. The first session focused on the definition and properties of a wave; the second session focused on the evolution of a wave in time and space and its graphical representation; the third session focused on superposition principle and interference.

3.2. Classroom observations
We conducted unstructured classroom observations, taking note of students’ difficulties, questions and doubts. In both the first and second implementation, we found that most students believe that, for a given medium, wavelength and frequency can change independently from each other and do not recognize, instead, that the propagation speed remains constant. Students always draw sound waves in three dimensions using circular wave fronts, but are unable to relate this representation to pressure variations in space and time or to produce and make sense of the graph of a sound wave. Moreover, they think that the frequency can affect the speed of the wave and, in general, don’t see a clear distinction between the concepts of frequency and propagation speed of a wave. Students are unfamiliar with the concept of phase, are not able to define what a phase is and to draw two waves with different phases. They are even more hesitant about the idea of coherence, which sometimes goes totally unmentioned in the discussion of interference, while other times is identified with monochromaticity. Eventually, some students refer to the wave profile as “the trajectory that the wave has to travel”. So if the amplitude increases, the wave “has to travel further and therefore it goes faster”. Hence, the reported naïve representation of the photon as a particle traveling on a sinusoidal path [32, 35] might have its precursor in this misconception.

3.3. The questionnaire
We started from literature on waves-related difficulties to develop a multiple-choice questionnaire. We administered it to the students before and after the activity. Students were given approximately 15 minutes to complete the questionnaire. The test was informally content-validated by the teachers before being administered.

In the first implementation, the test was composed of 10 questions. We assigned one point to each correct answer. No penalty for wrong or blank answers. The pre-test had an average score of 5.3/10 with standard deviation of 1.4; the post-test had an average score of 7.5/10 with standard deviation of 1.4. The effect size calculated via the Cohen’s d is 1.50 (large) with a confidence interval of 0.3. The reliability estimated via the phi coefficient [36-38] gives φ=0.22. The distribution of the results is shown in figure 1.

No items reported a negative discrimination index and most of them were above 0.3.

In the second implementation, we added five more questions based on our preliminary findings. The pre-test had an average score of 3.9/15 with standard deviation of 1.6; the post-test had an average score of 6.8/15 with standard deviation of 2.6. The effect size calculated via the Cohen’s d is 1.35 (large) with a confidence interval of 0.4. The reliability estimated via the phi coefficient [36-38] gives φ=0.53. The distribution of the results is shown in figure 2.

Except for one item, which is going to be reformulated in successive versions due to ambiguous wording, no other item reported a negative discrimination index and most of them were above 0.3.

The analysis of the distractors reveals that the most common naïve conceptions (distractors selected by more than one third of the students) are:
• An increase of the frequency leads to an increase in the propagation speed.
• Monochromaticity is necessary to observe interference.
• If one of the slits in Young double slit experiment is closed, the interference pattern is split in half (in the first version) or dimmed (in the second implementation).
• The wave front of a sound wave is composed of all the points at the same frequency (this question was not present in the first version of the test).

We report below an excerpt from the questionnaire:
A particle of dust is floating in the air in front of a loudspeaker. When the loudspeaker starts emitting sound, the particle:
A) Moves away with sinusoidal motion.
B) Is swept away.
C) Oscillates transversally (up and down).
D) Oscillates longitudinally (back and forth).

To increase the propagation speed of a wave in an oscillating rope, I need to:
A) Increase the amplitude of the shake.
B) Increase the frequency of the shake.
C) Use a rope made of a different material.
D) Make the experiment in the absence of air.

The effect of shaking a rope faster is that of:
A) Decreasing the vertical displacement of each point from equilibrium.
B) Decreasing the time it takes for the wave to reach the other end of the rope.
C) Decreasing the distance between two consecutive crests.
D) Increasing the intensity of the perturbation.

![Figure 1. Score distribution of the pre- (blue) and post-test (green) in the first implementation.](image)
3.4. The concept map

In addition to the test, we provided students with a list of words and asked them to construct a concept map.

In the first implementation, students constructed their maps in groups at the beginning of the activity (about 20 minutes), and successively revised and expanded their maps at the end of each session (about 10 minutes). However, students did not like the task, especially the revision part. So, in the second implementation, we turned it into an individual task and asked them to construct a map at the beginning of the activity and then to produce another one from scratch at the end of the activity (about 15 minutes each time). Nevertheless, students kept protesting against the task.

In the first implementation, since the map was a group work, we only evaluated it qualitatively. In the second implementation, we performed a quantitative evaluation as well. We decided to use two different methods to evaluate students’ concept maps.

The first method is a variant of the relation evaluation [39-41]. It consists in assigning each proposition a score of 0 (wrong), 0.5 (partially correct/incomplete) or 1 (correct and complete) and then sum up the scores for all propositions. The average score for the initial concept map is 11.2 with standard deviation of 4.6, and the average score for the final concept map is 16.2 with standard deviation of 5.8 (see figure 3).

For the second method, we first identified the crucial or core concepts explored in the activity, then we assigned each concept a score of 0 (wrong), 0.5 (partially correct) or 1 (correct) whenever it appears in the map. This allows us both to check how many of the core concepts are actually included in each map (see figure 4), and to evaluate the distribution of each concept across all the maps (see figure 5). The average number of concepts present in the initial map is 0.6/7 with standard deviation of 0.5, in the final map it is 1.4/7 with standard deviation of 1.3.

The Pearson product moment correlation coefficient between the two methods is high (0.6), while the correlation between each method and the questionnaire is medium (0.4).

With respect to the qualitative evaluation, we found that many students categorize waves in “mechanical, electromagnetic and sound waves” and regard harmonic and stationary waves as a subset of sound waves. Furthermore, many students classify “interference” amongst wave properties rather than among the associated phenomena, and write that waves can be constructive or destructive. Only a few students associate “pressure” to “sound” or link the word “medium” to “velocity” or “speed”.

Figure 2. Score distribution of the pre- (blue) and post-test (green) in the second implementation.
Figure 3. Score distribution for the pre- (blue) and post-maps (green), according to the relation method.

Figure 4. Number of core concepts found in students’ pre- (blue) and post-maps (green).
Figure 5. Distribution of core concepts in the pre- (blue) and post-maps (green): A) Dependence of the propagation speed on the medium; B) Relationship between wavelength and number of nodes in a stationary wave; C) Pressure as the oscillating quantity in a sound wave; D) Relationship between amplitude and energy; E) Transport of energy, not matter. F) Constructive/destructive interference as a consequence of the superposition principle; G) Coherence of the source in Young double slit experiment.

Figure 6. Is this picture misleading? (Reprint from [42])

4. Book analysis
To investigate whether the content presentation in textbooks may play a role in the development and consolidation of students’ naïve conceptions, we qualitatively examined chapters on wave-like phenomena from three popular textbooks: [42-44].

Two of them devote a whole chapter to sound waves and introduce stationary waves in this context, in accordance with what we found in the students’ maps. Moreover, all books discuss the properties and equation of waves in relation to the specific example of a wave on a rope, with little emphasis on the generalization to other cases in which the oscillating quantity does not correspond to vertical displacement from equilibrium. One of the books explicitly associates the sinusoidal profile of the wave equation to the sinusoidal movement of a shaken rope (see figure 6). This may partly account for students’ difficulties in generalizing wave properties and their graphical representation to the case of longitudinal waves.

None of the books pays much attention to coherence, which is a central concept also in quantum physics. On the other hand, all of the books present Young double slit experiment with monochromatic light and one of them explicitly states that interference can only be observed with monochromatic radiation. Only one of the books mentions the possibility to observe interference also with white (or broadband) light.

5. Discussion and future directions
Our work during the school year 2016/2017 allowed us to get in contact with teachers and scholastic institutions and to familiarize with the constraints and organizational difficulties of school settings, so that we can better arrange our planning for the next phase of the research.

Aside from students’ strongly negative reaction to map construction task, teachers and students generally exhibited a very positive attitude towards the activity. Almost all teachers spontaneously commented that they were quite surprised by the engagement displayed by shy or weak students during
classroom discussions and peer interaction. The impact of the proposed activities on students’ learning is highlighted by the general improvement both in the questionnaire and in the design of a concept map. We were also able to identify some shortcomings of our protocol and find ways to improve the quality and validity of our data. Namely, we need to better organize and coordinate our timing with schools in order to maximize the usefulness and effectiveness of our intervention. Besides we plan to improve the wording of some questions from the test and to follow a more rigorous validation procedure. We are going to revise our problems to take into account our preliminary findings and to allow teachers to master class discussion even without the researcher’s aid. Since students do not appreciate the map construction task, we will propose it only once, at the end of the activity. Moreover, we will collect background information on the materials, techniques and exercises proposed by teachers when addressing the topic in their classes.

So far we used mostly a quantitative approach to establish whether and to what extent the collective solution and discussion of our problems is helpful in improving learning outcomes. In order to understand the reason why such intervention is effective, we need to know what are the cognitive processes and learning strategies that students engage in, while working out our problems. To investigate this issue, we should resort to a more qualitative analysis. On one hand, we want to interview selected students on their questionnaire after the activity, to inquire as to whether they changed their answers pre- to post-test and why. On the other hand, we want to record classroom discussions and carry out a thematic content analysis [45, 46] to understand how students interact and compare their ideas. An example of this kind of work can be found in Bungum, Bøe and Henriksen [47].

6. References

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