Evidence of embodied cognition about wave propagation

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Abstract. That students think of wavepulses as if throwing balls down a long taut spring is well established. Typical questions involve students imagining the spring already pulled taut; a different scenario would imagine them pulling the spring tight first. This situation creates a different baseline of physical experience from which to reason. For example, it provides a physical experience in which tension is a relevant measure in the system. We investigated the effects of students pulling the spring (or not) in interviews after instruction. We also wrote two surveys, each giving a different physical description of a typical problem. From interviews, we find evidence that a different embodiment of the problem affects students' responses. In surveys, with students asked to imagine different situations, we found no such evidence.

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INTRODUCTION

Consider a long, taut spring on which one creates a short wavepulse by flicking one's hand up and down once. Past results [1, 2] have shown that students have difficulties with how one affects the speed of a propagating wave - is it with a hand motion of a faster or larger flick of the wrist, or by changing the spring to have a different tension or mass density? Results have been described in some detail using a variety of models of learning [3, 4].

A central problem when modeling the situation using multiple methods is to ask the question of what drives student thinking. In our previous work, the issue often seemed to be the physicality with which students responded to the question - they would flick their wrists, and even use gestures as grammatical stand-ins: "I would [quicker flick], I wouldn't be like [slower flick]" [4]. The central role of gestures in students' responses suggested that the body was playing a meaningful role in how they arrived at their answer. These results are consistent with the results of gesture analysis [5] and the growing field of embodied cognition.

In the original studies on students' understanding of wave propagation, we asked a very basic question about a wavepulse on a spring (shown in figure 1). In interviews with this question, we gave students the picture of the hand and spring, but not an actual spring. We were interested in the idea that one's engagement with the real physical object might play a role in the responses given to a well-studied physics problem.

When considering how an experiment with the actual spring in hand might affect student thinking, we realized that several possible beginning conditions were available to us. We might have students be handed a taut spring, flick their wrist once, and then answer the question about how to change wave speed. In this situation, we would most closely recreate the original interview situation. Or, we might have students take a loose spring, lying on the ground, and pull it tight, only to then flick their wrist, and finally answer the question about wave speed. In this situation, students' first physical engagement with the system (and their first time of changing the system) would involve tension, not the flick of the wrist. It was our guess that this physical activity would not consciously affect their thinking, but might lead them to think differently about the physics.

To test this hypothesis, we carried out a pilot study of five interviews (to explore the space of responses) and a written survey study with 82 students (to observe the prevalence of each response). We found some evidence to support our prediction that students would act differently depending on the way they embodied the problem, particularly in the interview activities. In particular, we were working with calculus-based introductory physics students who had just had instruction on wave propagation, both in lab and lecture, a week or two before. There was strong evidence to suggest that certain forms of mathematical reasoning about memorized formulas played a role in students' responses - though there is also evidence that how students embodied the problem affected their mathematical reasoning.

EVIDENCE OF EMBODIMENT AFFECTING INTERVIEW RESULTS

We designed interview tasks to allow us to observe differences in how physical actions affected student responses. The interview situation concerned a long spring, clamped at one end to a distant wall.

Two different conditions were tested. In the first, three students picked up a relaxed spring and pulled it tight

FIGURE 1. A hand creates a wave pulse which propagates down the spring towards the opposite end, where it is clamped.

(pulling tight condition). In the second, two students were handed a spring already pulled tight (already taut condition). Students were given the following instructions:

1. Students were asked to look at figure 1 and told to explain what they see.
2. Upon explanation of figure 1, students was asked how they would recreate the image, and to follow through with their stated method of creation.
3. Students were asked to describe what they saw, and if it had the desired effect.
4. Students were asked how they could make it so the pulse reached the wall in less time. After responding, they were asked for an explanation.
5. Last, students were asked how they could make it so the pulse reached the wall in more time. After responding, they were asked for an explanation, and the interview was completed.

The most important aspects of the interview were the answers the students gave to questions 4 and 5. Student responses for questions 1, 2, and 3 are not discussed.

Each student interview provided a unique case study of how students embody the problem. With such a limited sample size, however, major patterns cannot be identified. Instead, we organize the results according to common trends we saw in the interviews.

Students' answer first, justify later

Students generally answered the interviewer question without much explanation. Only when asked did they elaborate. Thus, we assume that the answers given were more instinctual, as the explanations were given after the fact. A common phrasing of question 4 was, "If I were to ask you what you could do so that the pulse reached the table in less time, how would you think you could do that?" Responses given were (with interview condition):

- Algernon: "Um... pull it tighter." (pulling tight)
- Benedict: "Uh... Stretch the spring out?" (pulling tight)
- Carson: "Well, if, first try – I would try moving faster, harder, different..." (pulling tight)
- Derrick: "[backs up to the opposite wall, pulling the spring] Increase the tension in the spring." (already taut)
- Emily: "I'd flick it harder? So that the velocity is higher?" (already taut)

Students in both conditions gave a correct response (about tension), and one student in each condition gave the most common incorrect response (about a hand flick). But, Algernon and Benedict, in the "pulling tight" condition, gave embodied responses related to the role of the hand when changing the tension, while Derrick, in the "already taut" condition, changed the tension by moving his whole body and backing up.

Only when the interviewer asked "why do you think that?" or "why do you say that?" did the students respond in greater detail. Benedict gave a quick and concise response, saying "Because changing the tension in the spring is changing the medium that the wave is moving through, which would change the speed at which the wave moves."

The other students took longer to answer. Algernon struggled at first: "Because the, because then [opens left hand and holds it up, as if holding an object / continues until "pulled tighter"] the medium is, I guess, less, I forget the technical term for it, but since it's pulled tighter, um, the wave has to travel through like [puts the spring in the left hand, uses right hand to recreate a similar gesture as before, holding his hand up and slightly open, as if gripping] uh, like it increases the speed. [closes hand] I don't know how to explain it, but I just know it's like that."

Carson first struggled to respond. His original explanation was, "Um, well I'm not exactly sure how I would change it, like, but, I know I would need it to travel faster, so, I think (incoherent). *PAUSE (4)* Just trying to think it out for a second. *PAUSE (9)*." He then used a mathematical response (described below) and finally, after interacting with the system, changed his answer to talk about the tension in the spring.

Reaching toward math

Everyone but Benedict used mathematical explanations at some point. Algernon reached for an incorrect mathematical explanation to explain the effect of greater tension. He said, "by doing this, um, it decreases the wavelength. And v equals lambda f, so, it'll increase, it'll sorta increase the wavelength. If the frequency stays the same, and the wavelength goes up, then the velocity would have to go up too." It is unclear how pulling tighter affected the wavelength, though.

Carson asked "Velocity is frequency times wavelength?", suggesting he was unsure of his answer. He connected his original response of a "faster, harder, different" hand motion to the idea that "it would probably be a shorter wavelength." Twice, he referred to equations from class, saying "I'm trying to remember the equations from this last week" and "I can't remember all those equations off the top of my head."

Derrick elaborated on his original response by saying, "Because the velocity of the wave and, I mean [points, with his left hand, to the portion of the spring nearest his right hand which holds the spring], you know, stretching it out like this is equal to the root of the tension over the linear mass density. So if you increase the tension in the spring [pulls the spring back slightly] it's going to increase the velocity of the wave." Derrick connected his physical action (backing up) with its effect (changing the tension) and made described it as consistent with the mathematics. It is unclear if he had this idea before he backed up to increase the tension, though.

Emily also used mathematical equations. She explained her original answer about a harder wrist flick by saying, "because it would be traveling faster," and gave no further explanation to question 4. When she answered question 5, she had played a little with the spring. At this point, she answered that changes to the tension would affect the speed. After saying "decreasing the tension" would make for a slower pulse, she said, "Because we had a formula that said v equals the square root of t over mu." It seemed that the mathematical formula helped her arrive at her new answer to question 5.

In sum, the two who were handed an already taut spring both used the correct formula (relating tension, mass density, and velocity) at some point in their responses, while those who pulled the spring tight either did not use any formula or focused on wavelength and frequency. We would have expected the physical situation to lead to mathematical explanations using tension in the "pulling tight" situation, as well.

Evidence of embodiment

All students talked about the tension of the spring, at the latest after they interacted with the system

To perfectly match our hypothesis that physical experience affects students' responses, students who pulled the spring tight would have answered talking about tension, and students handed the taut spring would have been more likely to give the common incorrect response that the wrist flick affects speed [2]. The data are more variable than this, but still show evidence of different kinds of embodiment. In the pulling tight interview condition, Algernon and Benedict both immediately responded about tension in the spring while standing still (suggesting that the changes would occur without changing path length). In the already-taut condition, Derrick used path length to affect tension.

Two students changed their answers as they interacted with the system. Carson, after talking about mathematics, suddenly changed his answer about the system to say, "Uh. I could probably stretch it out more." This comes after he tried several pulses that matched his prediction about the hand flick affecting wave speed. Interaction with the system helped him change his answer. Emily also gave a different explanation after she interacted with the system. These results suggest that some element of the physical activity affected the students' thinking. Perhaps the prediction that a harder flick affects speed was not born out, so they went seeking new explanations, and the physical interaction with the spring provided ideas they would otherwise not have had.

NO EVIDENCE OF EMBODIMENT IN WRITTEN SURVEYS

We created a pair of survey questions to observe the prevalence of common responses to the pulling tight and already taut conditions of the wave propagation problem. The two opening statements are shown separately, followed by the shared text of each question.

Survey 1: Pulling Tight Imagine that there is a coiled up spring resting on the floor, attached at one end to a wall. You pick up the spring and take several steps back, pulling the spring taut.

Survey 2: Already-Taut Imagine that you are holding a spring that is pulled taut, attached at one end to a distant wall.

Shared You move your hand up and down, in a motion designed to create a pulse that moves down the spring. This pulse reaches the wall in some time t_0. What can you do so that the wave pulse reaches the wall in less time? Explain your reasoning as fully as is possible.

We predicted two results from this study. First, students given Survey 1 (pulling tight the spring) would be more likely to answer that the tension or length of the spring affects wave-pulse travel time down a spring. Second, students given Survey 2 (the already-taut spring) would be more likely to answer that the hand-motion affects wavepulse travel time down a spring. We did not take into account that Survey 2 included suggestive language ("pulled taut") which likely affected our results.

The surveys were administered roughly 1 1/2 months after instruction on wave propagation. Surveys such as this had been given either as formative assessments or as part of other research studies during the same semester. Students were randomly handed one survey, and were

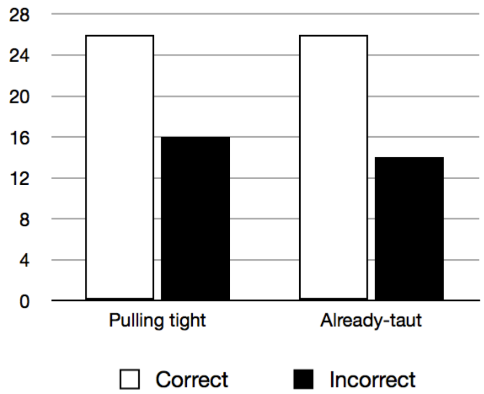

FIGURE 2. Student correctness on each survey.

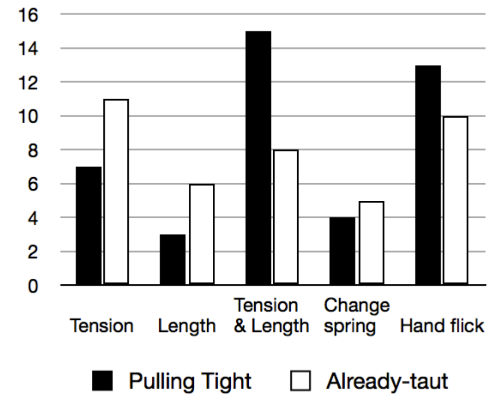

FIGURE 3. Explanations given by students on each survey.

not aware that others in the room were answering two different surveys. A total of 82 surveys were collected, half for each survey.

Results show no difference in responses

Our data found no meaningful differences between the two surveys. We found that 59 of 82 (72%) survey responses involved changing the medium, either by changing the tension, path length, or the spring itself. Of these 59, 29 (49%) answered Survey 1 and 30 (51%) answered Survey 2. We found that 23 of 82 (28%) responses involved changing the hand motion employed to create the wave pulse. Of these 23, 13 (57%) were from Survey 1 and 10 (43%) were from Survey 2. As similar as these results were, we did not carry out further statistical analysis.

Further representations of the data again show little difference (see figures 2 and 3). Figure 2 shows that there was no difference, overall, in the number of correct and incorrect responses among the students (numbers do not add to 41 in each case because some students gave multiple answers, both correct and incorrect.) Responses were labeled incorrect if they involved decreasing the tension or path length, or if they involved affecting the motion of the hand (either making a bigger or smaller flick). Notably, using the right kind of reasoning (about tension) was still counted as incorrect when appropriate. Figure 3 shows the type of response that was given. Correct answers were given for responses which involved increasing the spring tension or path length, or changing the medium (such as by changing the spring).

In sum, we find that the different phrasing of the question played no major role. Most likely, Survey 2 was not sufficiently different from Survey 1 due to the use of the phrase "pulled taut." Also, students may not have been sufficiently primed to think about the different kinds of embodiment in each survey. It could also be that students after instruction are not likely to answer the question in the ways we predicted and that instruction affects how students interpret the embodied situation described by a problem.

DISCUSSION

This two-part study was designed to see if physical engagement with a system would affect students' thinking, and whether verbal descriptions of different physical situations would play a similar role.

We found that some students in the test condition (pulling a spring taut) answered immediately by thinking about tension in the system, while the other students did not, and that all students gave explanations based on tension by the time the interview was complete. Our survey results were inconclusive. We found no major differences in the two populations and believe the primary reason is for lack of difference in the embodiment of the two questions.

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