Eye-movement study of mechanics problem solving using multimodal options

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Abstract. We used an eye-tracking method to investigate students' approaches to solving a physics task using various representations. Eight upper-secondary school students from Finland took part in the study. We found that students who preferred either the text or graph representations watched the options differently, but they used both representations to be sure of their solution. Transitions between text and graph alternatives were different for students preferring either text or graph representations. Interviews revealed typical misconceptions about the concept of force. Implications for physics instruction are presented.

1 Introduction

In this study, we used an eye-tracking method to investigate students' problem-solving processes while they were completing a multiple-choice physics test. We were especially interested in how the strategies depended on whether students preferred text or graph representations of the multiple-choice alternatives. Eye-tracking studies base their interpretation of gaze allocation on the eye-mind hypothesis [1], according to which a person's attention is focused on the point of fixation. Therefore, eye movements have a spatiotemporal relationship to visual information, and gaze allocation provides indirect data regarding a person's cognitive process. In contrast to some studies showing the shortcomings of the eye-mind hypothesis [2], other neurophysiological studies support the hypothesis [3]. For instance, in studies using multiple-choice tasks, attention and gaze are closely related [4].

Recent studies of students' understanding of graphs, both with and without eye tracking (see [5] for review), show that students have difficulty interpreting graphs. Studies using multiple-choice questions in which choices are represented in various ways (e.g., text of graph) show that students' gaze allocation seems to depend on the type of representation used [6]. Based on the dual representation paradigm, researchers have displayed two graph types at the same time and compared how different graph formats (line or bar) effect students' test results. They found that participants shifted their graph preference depending on task type and that participants used both graph types during the tasks to verify their answers [7].

In this study, we similarly use the dual representation paradigm and explore students' strategies when multiple-choice alternatives are provided in both text and graph formats. The students' preferences for the representations are taken in account as well. Even though the multiple choices are represented differently, we assume that these representations are informationally equivalent in terms of answering the question. Two representations are termed informationally equivalent when they display the same relationships between the same objects [7].

According to Mayer's cognitive theory of multimedia learning [8], humans process visual information via a visual channel and auditory information via a verbal channel. Also, humans often convert printed text into sound so that it can be processed in the verbal working memory. Therefore, we may consider students to be processing the text alternatives of the multiple-choice test in the verbal memory and graph alternatives in the visual memory. Prior research has focused on presenting multiple-choice alternatives in either text or graph form, and it is unknown whether providing these alternatives in both text and graph form in the same question side by side affects how students process items. Our aim is to investigate how students solve multiple-choice problems when alternatives are provided in two forms. Our research questions are as follows:

1) How does students' gaze allocation differ depending on their graph/text preference?
2) How do transitions between text and graph alternatives differ depending on students' graph/text preferences?
3) How do students defend their choices?

2 **Methods**

2.1 Data collection

The student participants were chosen from a upper secondary school in Finland. They were completing the first and fifth physics courses [9], both of which deal with mechanics. Their average age was 17 years. The students' parents signed a consent letter.

Before the eye-tracking test, students answered a nine-question multiple-choice pre-test to determine their conceptions of Newton's First and Second Laws. Based on the test results, a nine-student sample was chosen (very success full, success full or unsuccessful).

Eye-tracking data collection was performed during school days in spring of 2018. The eye-tracking device used in this study was the SMI RED250mobile. Prior to data collection, the eye-tracking unit was set to a 250 Hz sampling frequency, the fixation minimum period was 50 ms and the saccade was determined by an eye movement speed of at least 40°/s. The students completed the test independently on a computer. Before using the device, it was calibrated to determine the positions of the eyes of the participating student. The multiple-choice questions appeared on the screen one by one. Students selected the alternative they thought to be the correct answer with the mouse, after which a new question appeared on the screen, and they could not return to the previous tasks. Because of unstable eye track results, the data for one student were not used in this study. Ultimately, we had a sample size of eight students.

On the eye-tracking test, we had four qualitative items related to Newton's First and Second Laws. These items were based on the Force Concept Inventory (FCI) test [10] and the Representational variant of the Force Concept Inventory (R-FCI) test [11]. The layouts of the tasks were similar. The multiple-choice alternatives were presented in both the text and graph representations. For every item, the stem was presented in text form on the left side of the screen. Items were arranged in pairs related to same physics concepts, and they varied so that in one item, the text was on the left side and the graph on the right side, while in the other paired item, the order was reversed. Figure 3a depicts one item (a woman pushing a box) in which the text alternatives are on the left and the corresponding graph alternatives are on the right. Figure 3b shows a similar item (a man pushing a trolley) in which the text and graph alternatives are in reverse order as compared to the woman-pushing-a-box item. The reason for this text/graph rotation was to determine whether students use the representation option (graph or text) they prefer or choose the alternatives that are closest to the stem. Otherwise, the layouts of the tasks were similar because there is evidence that different spatial layouts affect problem solvers' gaze movement [12]. In all items, only one out of the five multiple-choice alternatives was correct, and the remaining alternatives were distractors related to typical student misconceptions.

Students' graph-text preferences were investigated with a five-point Likert scale questionnaire. The four questions used were "I am good at reading graphs", "I feel confident in reading graphs", "Generally, I prefer text form to graph form" and "Generally, I prefer graph form to text form." The test idea was adopted from [7], in which the researchers used a similar short questionnaire to determine students' preferences for line or bar graphs. The graph-text preference measure was calculated as the difference between the preference scores for the questions.

After the eye-tracking tasks, students were interviewed. During these interviews, they were shown the eye-tracking items on a computer screen, and the interviewer asked, "Why did you choose that alternative?", "Which alternative did you immediately recognize as incorrect answer?" and "Did you have the second candidate, or did you hesitate to choose the answer you chose?" Other questions depended on a student's responses to the previous interview questions. After this, the students were shown their gaze plot videos. The students commented on their solution processes, and the interviewer asked, e.g., "What was your strategy in solving the task?", "Why didn't you look at that alternative at all?", "Why did you look so much at this specific alternative?" and "When you observed your record from the gaze plot video, was there anything surprising for you?"

2.2 Data analysis

For the analysis of the eye-tracking data, we generated heat maps for each student and each task with SMI BeGaze software. Heat maps show how much a subject has viewed certain areas of the task, words or images when solving the problems. We created the areas of interest (AOIs) with the SMI Experiment Center software program. For every item, the stem and each multiple-choice alternative was a separate AOI (see figure 1). We created these AOIs to investigate the transitions between the AOIs and thus obtain information about the transitions between the stem and the various alternatives. Students did not see the AOIs at any stage of the test.

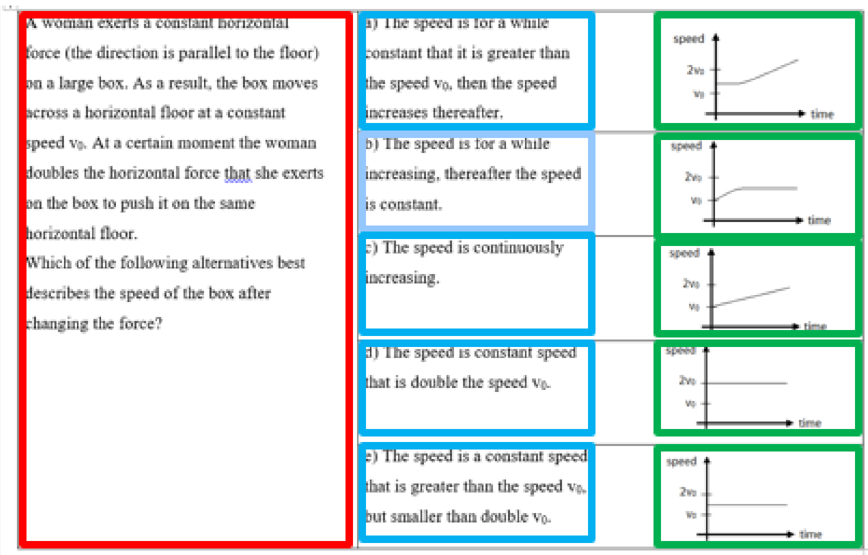

Figure 1. AOIs of the task.

To analyse students' gaze transitions between various AOIs, we produced transition matrices for each student and each task (i.e., 8x4 = 32 transition matrices) based on students' fixations on the AOIs. The columns and the rows of the transition matrix represent the AOIs in the region, and the cells in the matrix indicate the number of transitions from the row AOI to the column AOI. For example, as seen in Figure 2, a student performed three transitions from option d) in graph representation to option d) in text representation.

p4	graph e	graph d	graph c	graph b	graph a	text e	text d	text c	text b	text a	stem
graph e						1					
graph d	1						3				
graph c		1									
graph b			1								
graph a				1							
text e		1									1
text d						1					1
text c											
text b											
text a											1
stem		2			1						

Figure 2. Student #4 transition matrix for the "woman pushing a box" task.

3 Results

3.1 Graph-text preference in heat maps

Heat maps (Figure 3) show that Student #4, who prefers graphs generally, looked more at the graph alternatives independently, whether the graphs were on the right or left side on the screen. The student also looked at some text alternatives, but not as much as at the graph alternatives. For the "woman pushing a box" task, the student looked most at the text alternative (d), which he/she chose as his/her answer. In this task, the student seems to have the typical misconception that if the force is doubled, the speed will also be twice as large. However, the "man trolley" task shows that the student's conception is not fixed because there, the student has chosen alternative (a), in which the speed is not doubled. The heat map shows that the student has almost discarded the double-speed alternative (d).

a) woman pushing a box task b) man trolley task

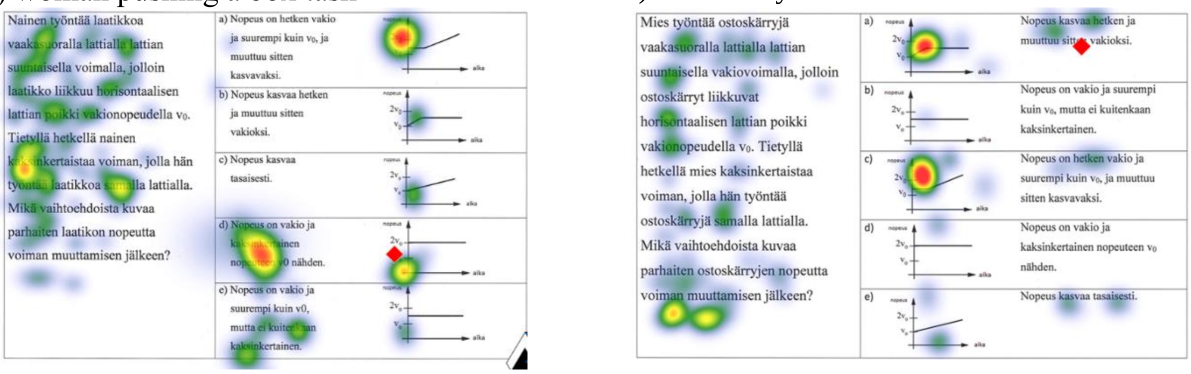

Figure 3. Heat maps for two tasks completed by a student (#4) preferring graphs.

A text-oriented student's (#2) heat map for the "woman pushing a box" problem (Figure 4) show that he/she has mainly looked at the text alternatives. The student has chosen the incorrect alternative (e), in which the speed of the box is constant and larger than the original value. This student has also checked his or her "correct" thinking by looking at the corresponding graph alternative (e). Because the student has chosen the corresponding alternative in the "man pushing trolley" task, he/she seems to truly believe that although the force is double, the speed cannot be double, though it is larger than the initial speed.

a) woman pushing a box task b) man trolley task

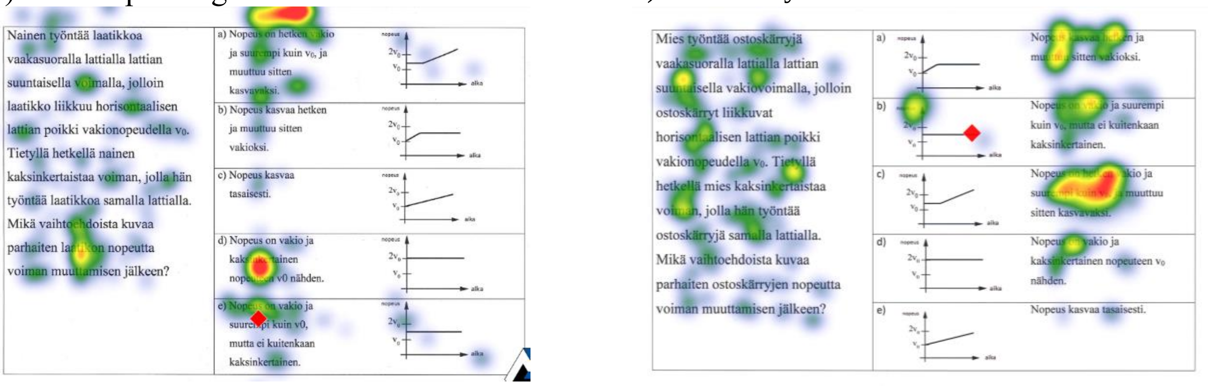

Figure 4. A text-oriented student's (#2) heat maps for two similar tasks with different layouts.

3.2 Graph-text preference in transitions between AOIs

We first examined the number of transitions from the stem to the options. This measure can be interpreted as the number of times a student has to reread the stem to connect it with the options and how difficult or easy it is for that student to remember the stem.

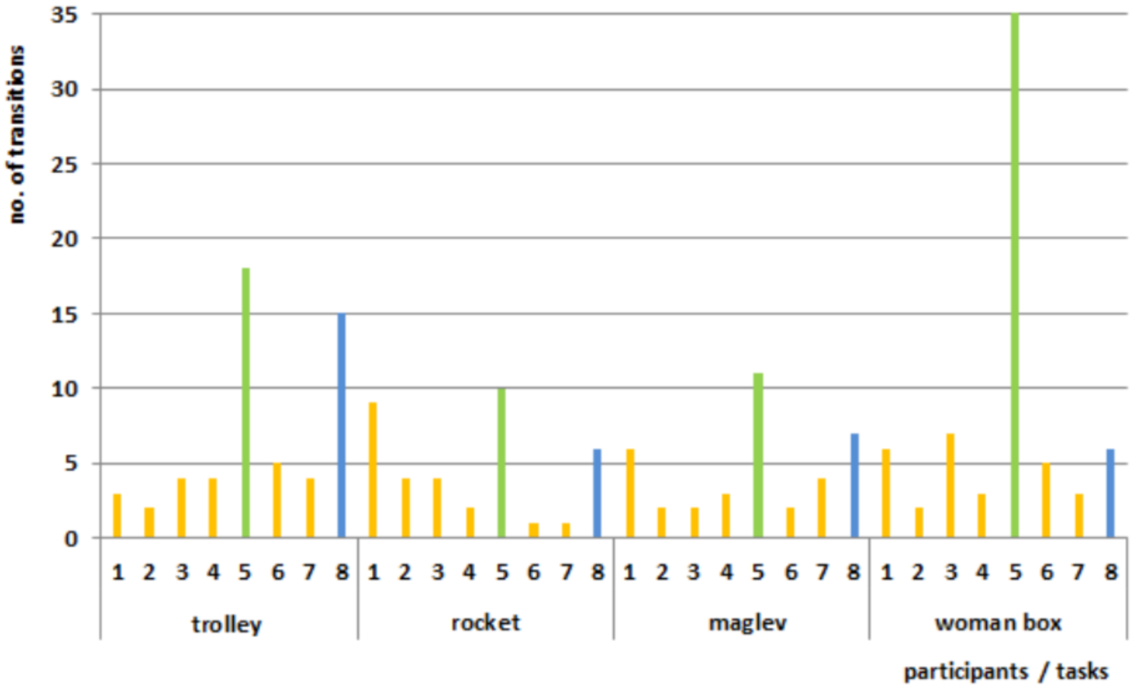

Figure 5. Number of transitions from stem to alternatives.

We found that in 80% of cases, there were, at maximum, seven transitions and that in 60% of cases, there was a maximum of five transitions. As we can see from Figure 5, two students (5 and 8) showed more transitions from the stem to the options. Student #5 had many more, mostly for the "man pushing the trolley" and "woman pushing the box" tasks. This student also received the best results on the test.

On the other hand, Student #8 received the worst results on the test. He solved none of the eye-tracking items correctly.

Secondly, we considered the transitions between different options, specifically from a text option to a graph option and vice versa. We also calculated the transitions within the option types, that is, from a text option to another text option and from a graph option to another graph option. Figure 6 shows the numbers of these three types of transitions for each student in all four tasks. The total number of transitions equals 100%. Transitions between the same kind of representation can suggest checking the options during the decision-making process, while transitions between different kinds of representations can suggest comparisons between representations.

For almost all tasks and all students, transitions between different representations are most common, and all students prefer these transitions for almost all tasks. Students 1, 2 and 3 stated on the questionnaire that they preferred text representation. Accordingly, Students 1 and 2 seems to have more text-to-text transitions for the woman and maglev tasks. For the rocket task, they have more graph-graph transitions. Student 6 stated no preference, though he showed a similar text-preferring approach. Despite claiming to prefer text representation, Student 3 only has more text-to-text transitions during the woman task. Student 4 stated a graph preference, and for all tasks he indeed prefers either graph-graph transitions or text-graph transitions.

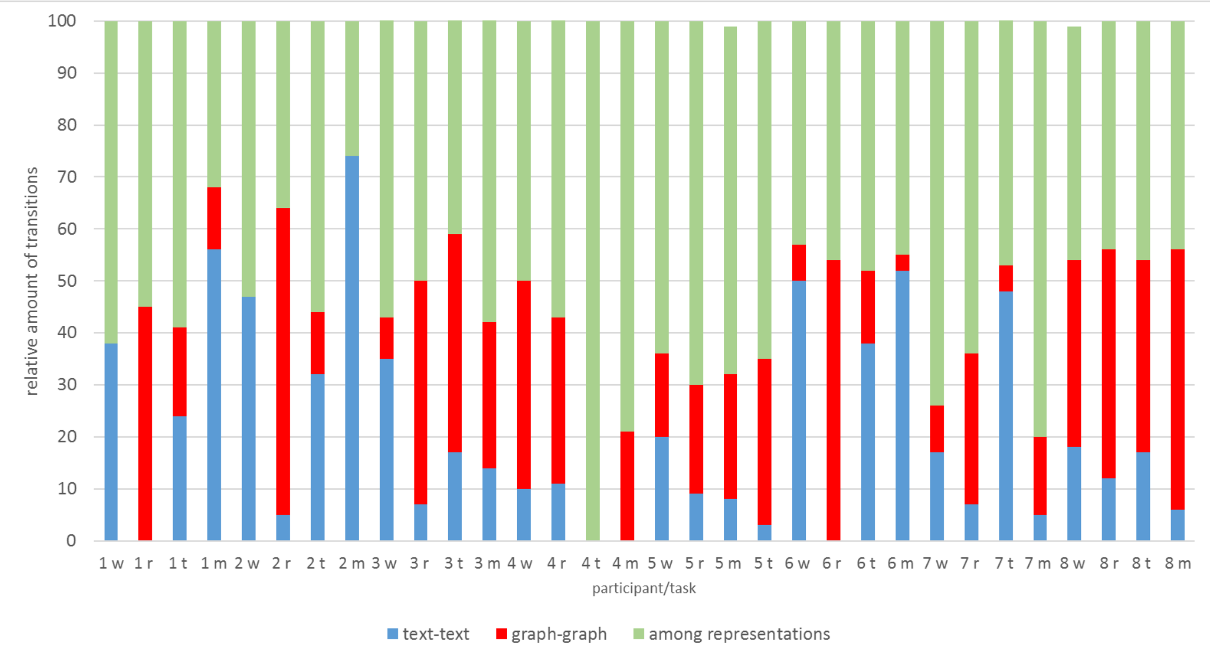

Figure 6. Transitions between different representations (green), between graph options (red) and between text options (blue) in the tasks. (tasks: m = maglev, w = woman, t = trolley, r = rocket)

Table 1 shows the percentages of the different transition types for different student groups. From the table, we can see that students who report preferring text format make more transitions between text options than between graph options. The students who prefer graph representations make more transitions between the graph alternatives. In all groups, the transitions between different representation types are the most common. All student groups show similar levels of graph-graph transitions (about 25% of all transitions). However, the group of students who prefer graphs make far fewer text-text transitions, and more transitions between different representation types. In contrast, students who prefer text make the fewest transitions between representation types.

Table 1. Percentage of transitions for students depending on their graph-text preferences.

	Transitions		
	text-text (%)	graph-graph (%)	between different representations (%)
prefer text	29	22	49
prefer graph	5	23	72
no preference	19	25	56

3.3 Students' reasons for their answers

In the interview, students were asked the reasons for their choices. The answers revealed the students' typical non-Newtonian conceptions. They said, for instance, that "when the force is doubled, then the speed has to be doubled as well". They believe that a constant force acting on an object will lead to a constant speed for the object. Also, they believe that motion requires force. When giving evidence for their choices, they used everyday language, such as "I thought that there would be a kind of small kick when the motor starts and then it would be constant" or simply "it is reasonable".

Some students used explicitly correct ideas and physics concepts in their explanations. They could reason, e.g., "since there are no other forces in the space, when the motor pushes the rocket, the rocket speed increases all the time" or "Uhm, because there are no external forces acting in space, I thought that when it is pulling all the time, then the speed will also increase all the time." Another student said, "I thought that because no forces act on it, when more force is applied, the speed will increase because if there were an equal force on the opposite direction, it would continue moving with constant force, but because only one force is acting, I thought that its speed would increase."

The students were astonished to see from the gaze plot how they had been looking at the problem: "This is cool! From here, you can see where I stopped reading." They were mostly unaware of where they had allocated their attention during the task: "I was really astonished that when I was reading the stem, I also looked at the graphs many times" or "I was astonished that I looked at the graphs so little."

Some students could explain their transition behaviour, e.g., by saying that their problem solving process involves considering various alternatives: "I first read the stem and started to go through the alternatives." Alternatively, they pick the best alternative and then check the corresponding graph/text option: "When reading the stem, I was already thinking about which might be the best alternative" or "By the end of the stem, I thought that the alternative that was constant would be my answer."

4 Conclusion

Our aim was to investigate students' gaze allocation on multiple choice test when options are given both in text and graph form. Heat maps show that students' gaze allocation depends on their graph/text preferences. For instance, students who prefer graph representation tend to look more often at the graph alternatives than the text alternatives. Also, transitions between text and graph AOIs depend on students' graph/text preferences. Student's self-appraisal of their graph/text preferences may be wrong, but the eye-tracking results show their actual preferences. Often, students defended their choices by using non-Newtonian conceptions and everyday language, seldom using physics concepts and laws.

In this study, graph and text stimuli were placed side by side in the area of each option. This situation likely confused some students and provided a hint to others. These students are novices. They are not used to solving physics problems with graph and text options. Generally speaking, graph and text stimuli are equivalent informationally when one masters how to interpret them correctly. The arrangement forced students to consider that the graph as equivalent to the text and vice versa.

This was an explorative case study, and the results cannot be generalised. However, they do suggest new research directions. In the future, we will collect additional data using the same questions and also questions addressing different physics areas to determine if there are any general patterns.

Teachers and researchers must remember students' preferences for graph and text representations. For some students, a graph alternative might be easier than a text alternative, and vice versa. Students should be taught to combine both representation types and given opportunities to practise this.

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