Students' Difficulties in Learning Physics from Dynamic and Interactive Visualizations

Rolf Ploetzner, Stefan Lippitsch, University of Education, Freiburg, Germany
rolf.ploetzner@ph-freiburg.de, stefan.lippitsch@ph-freiburg.de
Matthias Galmbacher, Dieter Heuer, University of Würzburg, Dep. of Physics, Germany
galmbach@physik.uni-wuerzburg.de, heuer@physik.uni-wuerzburg.de

Abstract: In two experimental studies we investigated whether students' difficulties in understanding line graphs in kinematics can be improved by means of dynamic representations. These representations were designed to help students in mentally bridging the gap between motion phenomena and abstract line graphs. In the first study, contrary to our expectations, the employed representations did not only not improve learning - but even impeded it. This finding was underpinned by the second study, in which almost no sign was found of students having internalized the relevant aspects of the dynamic representations. Because similar results have recently been found in other studies, we propose that research on learning with dynamic representations should not only focus on developing guidelines for the external design of representations but also on conceptualising learning strategies which can be taught to students and which help them to successfully process the information presented in the external representations.

Introduction

Physics education aims at helping students to view physics as a consistent system of concepts, principles, models, and techniques related to the physical world. For the past two decades, research on physics education has demonstrated that many students face severe difficulties in learning physics. Various factors may contribute to these difficulties. While some factors are considered to be intrinsic to the students, such as the students' preconceptions about physics, other factors are considered to be intrinsic to the way in which physics is taught.

In teaching physics, educators frequently employ different external representations which make different aspects of a physical situation or a physics concept salient, describe aspects of a physical situation or a physics concept which cannot be described by means of other representations, and complement each other in such a way that more complete representations result. Computers offer the additional opportunity to educators to take advantage of dynamic and interactive external representations to represent physical situations as well as physics concepts that change in time and space.

While the use of different external representations has the potential to improve the learning of physics, it also places various demands on students (for a collection of papers see Ploetzner & Lowe, 2004). For instance, students need to understand how information is encoded in each representation, how each representation is related to the physical world, and how information in one representation can be related to and transformed into information in another representation (e.g., Ainsworth, 1999). Dynamic representations demand students to process continuously changing information (e.g., Lowe, 2003) and if external representations are not only dynamic but also interactive, they require students to carefully prepare, execute, and evaluate their interactions (e.g., de Jong & van Joolingen, 1998).

One notorious problem in physics education is the students' difficulty in understanding line graphs. In this paper we describe two experimental studies. The first study aimed at improving students' comprehension of line graphs in kinematics by means of interactive simulations and dynamic representations. However, in accord with the findings of many other studies on learning with dynamic representations, the students faced severe difficulties in taking advantage of the information encoded in the dynamic representations. The second study aimed at identifying whether students make use of the information encoded in dynamic representations when solving kinematics problems.

Enriching Interactive Simulations in Physics with Iconic Representations

Line graphs such as time-position graphs, time-velocity graphs, and time-acceleration graphs visualize functional relations between time and kinematics concepts. The lower section of Figure 1 shows a time-position (left hand side), a time-velocity (middle), and a time-acceleration graph (right hand side) representing an object's motion.

In physics education, students are expected to acquire (1) the ability to construct a line graph that appropriately represents an object's motion, provided the description of the object's motion is given, and (2) the ability to interpret a line graph, i.e., to formulate an appropriate description of the motion underlying a line graph. In physics textbooks, very often line graphs are "developed" in three steps. In the first step, an object's motion is described by means of a text as well as by means of a picture. In the second step, values of a kinematics concept at various points in time are presented in a table. In the third step, the variable values as well as their interpolation are visualized in a coordinate plane.

Research on physics education has repeatedly demonstrated that very often students have severe difficulties in understanding line graphs (e.g., Berg & Smith, 1994; Scanlon, 1998). These difficulties apply to the construction of line graphs as well as to their interpretation. Even students who successfully construct line graphs in mathematics are often unable to take advantage of their knowledge in physics (e.g., Leinhardt, Zaslavsky & Stein, 1990). In the most frequently observed misinterpretation of line graphs in kinematics, students view line graphs as paths of motion regardless of which kinematics concepts are taken into account by the graphs (e.g., McDermott, Rosenquist & van Zee, 1987). Obviously, many students are hardly able to mentally bridge the gap between observable or simulated motion phenomena on the one hand and abstract line graphs on the other.
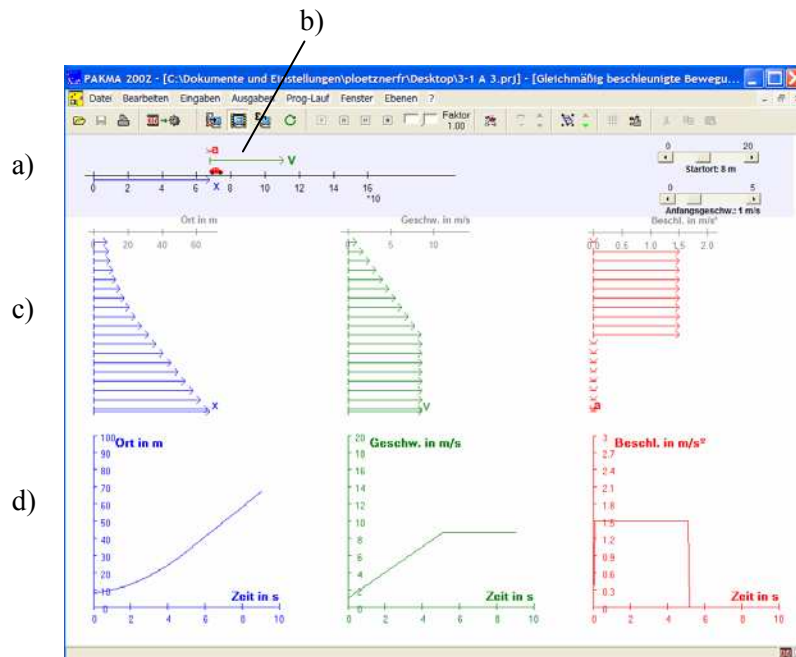
Figure 1. Dynamic representations in PAKMA: (a) simulations of motion phenomena, (b) iconic representations of kinematics concepts, (c) stamp diagrams, and (d) line graphs.

Is it possible to improve students' understanding of how motion phenomena and line graphs are related to each other by means of interactive simulations and dynamic representations? In order to investigate this question, we took advantage of the simulation program PAKMA (Heuer, 2002). Among other phenomena, PAKMA allows for the interactive simulation of motion phenomena. In comparison to textbooks, PAKMA offers the opportunity to visualize how different representations of kinematics concepts dynamically and synchronously change in time.

To help students understand how motion phenomena and line graphs are related to each other, four dynamic representations – exemplified in Figure 1 – are employed in PAKMA: (a) simulations of motion phenomena (abbreviated S), (b) dynamic and iconic representations of kinematics concepts which are superimposed on the simulated motion phenomena (abbreviated DIR), (c) dynamic stamp diagrams (abbreviated STAMPS), and (d) dynamic line graphs. Iconic representations correspond to vector representations of kinematics concepts such as position, velocity, acceleration, and force. Stamp diagrams result from stamping iconic representations in a coordinate plane at defined points in time. Line graphs correspond to the interpolation of the iconic representations'

heads in the stamp diagrams. In PAKMA, the simulation can be started and stopped interactively at any time, the simulation can be run continuously or frame by frame, and each representation can be faded in or out interactively.

Study 1

In an experimental study we investigated whether students' understanding of line graphs in kinematics improves depending on the dynamic representations made available to the students. We hypothesized that the availability of iconic representations of kinematics concepts superimposed on simulated motion phenomena (cf. Figure 1a and 1b) would make it easier for students to relate motion phenomena and line graphs (cf. Figure 1d) to each other than the mere availability of simulated motion phenomena and line graphs. We further hypothesized that the additional availability of stamp diagrams (cf. Figure 1c) would help students even more to relate motion phenomena and line graphs to each other.

Method
Design

Three groups were formed, who made use of three different simulation environments. In the first environment (S), various motion phenomena were interactively simulated and line graphs were dynamically displayed. In the second environment (S+DIR), dynamic and iconic representations of kinematics concepts were additionally superimposed on the simulations of the motion phenomena. In the third environment (S+DIR+STAMPS), dynamic stamp diagrams were also displayed.

Participants

Overall, 111 volunteer eleventh graders were randomly assigned to the groups: 39 students to group S, 33 students to group S+DIR, and 39 students to group S+DIR+STAMPS. The students had attended introductory classes on the kinematics concepts of position and velocity. While 54 students were girls, 57 students were boys. Girls and boys were approximately equally distributed across groups.

Learning Material

For each group investigated, the learning material comprised eight physics projects progressing from the two easier concepts position and velocity to the two more difficult concepts acceleration and force (cf. Reif & Allen, 1992). Each concept was addressed by two projects. Every project was made up of a worksheet and a simulation environment. The worksheet aimed at encouraging the students to make use of the corresponding simulation environment in a structured way. A worksheet always started with a text that described a motion phenomenon. Thereafter, various questions had to be answered by the students while making use of the simulation environment. For instance, students were asked to describe how a time-position graph changes in the simulation environment when an object's velocity is interactively altered. The questions were provided with information on how to run the simulation environment. Students were asked to write down their answers to the questions on the worksheet.

Procedure

Initially, the students took a pre-test to determine their knowledge in kinematics as well as their visual-spatial abilities (Raven, 1980). The pre-test addressed the students' knowledge about the kinematics concepts position, velocity, acceleration, and force. It consisted of 14 questions, the answers of which demanded the interpretation of line graphs. Next, the students worked individually on an example physics project in order to learn how to run the simulation environment. This project addressed an object's changing position in such a way that the students were able to focus on running the simulation environment. Thereafter, the students worked individually on the eight physics projects described above. For each student, the learning time was limited to 150 minutes. Finally, the students worked on a kinematics post-test which consisted of 30 questions, the answers of which demanded the interpretation of line graphs, as well as of 12 questions, the answers of which demanded the construction of line graphs.

Results

The students' performances in the pre-test are shown in Table 1. There are no significant differences between the groups. However, on average the students had significantly more success with test items concerning the easier concepts position and velocity than with test items concerning the more difficult concepts acceleration and force ($F = 794.1$, $df = 1,110$, $p < .001$).

Table 1. The means (M) and standard deviations (SD) of the relative solution frequencies in the pre-test.

	Simulation environment		
Kinematics concepts	S	S+DIR	S+DIR+STAMPS
Position and velocity	M = 67.9% (SD = 21.2%)	M = 66.3% (SD = 22.2%)	M = 69.2% (SD = 19.0%)
Acceleration and force	M = 26.6% (SD = 22.4%)	M = 26.5% (SD = 23.7%)	M = 31.1% (SD = 22.9%)
Overall	M = 47.3% (SD = 17.9%)	M = 46.4% (SD = 18.8%)	M = 50.2% (SD = 17.5%)

To analyze the students' learning performance, we computed the students' relative learning gain g (cf. Hake, 1998): $g = (\%Correct_{post\text{-}test} - \%Correct_{pre\text{-}test})/(100 - \%Correct_{pre\text{-}test})\ x\ 100$. By means of a median split, each group of students was divided into two subgroups: a group with low visual-spatial abilities and a group with high visual-spatial abilities. Figure 2 shows the relative learning gains with respect to the different kinematics concepts.

A multivariate analysis of variance did not reveal any significant differences between the groups of students across all kinematics concepts. While a univariate analysis of variance did not reveal significant differences between the groups of students with respect to the concepts position and velocity, it revealed significant differences with respect to the concepts acceleration and force ($F = 4.19$, $df = 2,105$, $p < .05$). Concerning the factor "simulation environment", however, these differences are diametrically opposed to our predictions: on average, those students who only had the simulated motion phenomena and the line graphs available received higher learning gains than those students who additionally had iconic representations and stamp diagrams available.

Students with low visual-spatial abilities accomplished significantly smaller learning gains with respect to the concepts acceleration and force than students with high visual-spatial abilities ($F = 4.78$, $df = 1,105$, $p < .05$). Although the interaction between the factors "simulation environment" and "visual-spatial ability" is statistically not significant, this is especially true for those students who had the iconic representations available without having the stamp diagrams available: these students performed even better in the pre-test than they did in the post-test.

Study 2

Contrary to all our expectations, dynamic iconic representations and stamp diagrams did not help students to better understand line graphs. With respect to the easier kinematics concepts position and velocity, the availability of these representations made no significant difference. With respect to the more difficult kinematics concepts acceleration and force, the availability of iconic representations and stamp diagrams even hindered learning. Although stamp diagrams partially compensated for the difficulties which were associated with iconic representations, they nevertheless did not improve learning beyond the learning gains which were achieved without iconic representations and stamp diagrams. Although these findings contradict our expectations, they are in accord with the findings of many other studies which demonstrate students' difficulties in learning from and making use of dynamic representations (for an overview see Bétrancourt & Tversky, 2000). In a second study, we aimed at identifying whether students make use of the information encoded in dynamic iconic representations during problem solving.

Method
Design

Two groups were formed who made use of two different simulation environments. While in one environment (S) various motion phenomena were interactively simulated and line graphs were dynamically displayed, in the other environment (S+DIR) dynamic and iconic representations of kinematics concepts were superimposed on the simulations of the motion phenomena.

Participants

Overall, 18 volunteering eleventh graders were randomly assigned to each group. The students had attended introductory classes on the kinematics concepts position and velocity. While 19 students were girls, 17 students were boys. Girls and boys were approximately equally distributed across groups.
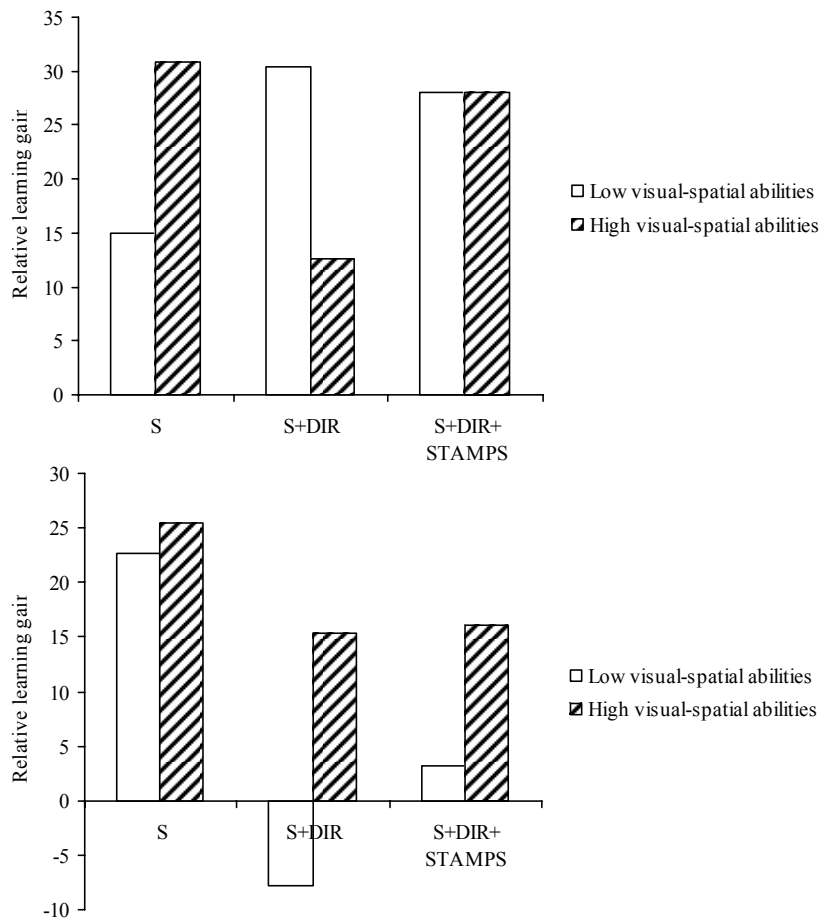
Figure 2. The relative learning gains with respect to the concepts position and velocity (above) and acceleration and force (below).

Learning Material

For each group investigated, the learning material comprised 14 physics projects progressing from the easier concepts to the more difficult concepts. Two projects were on position and time-position graphs, four on velocity and time-velocity graphs, four on acceleration and time-acceleration graphs, and four on force and time-force graphs. Again, every project was made up of a worksheet and a simulation environment which had to be processed by the students.

Procedure

Initially, the students took the same pre-test used in the first study to determine their knowledge in kinematics. Thereafter, the students worked individually on the 14 physics projects described above. For each student, the learning time was limited to 180 minutes. Next, the students worked individually on 6 kinematics problems without having access to the simulation environment. During problem-solving, the students were asked to think aloud (cf. Chi, 1997) and to write down their problem-solving attempts. The students' verbalizations as well as their problem-solving attempts were recorded on the computer. For each student, the problem-solving time was limited to 120 minutes. Before problem-solving took place, the students first watched a video demonstrating the verbalizations of a person solving a puzzle on the computer. Thereafter, the students exercised thinking aloud while solving a variation of the puzzle.

Results

There were no significant differences between groups in the pre-test: the students in both groups gave on average 36% correct answers to the questions. There were also no significant differences between groups in problem solving performance: while the students in group S solved on average 51% of the problems, the students in group S+DIR solved on average 53% of the problems. To assess whether students make use of the information encoded in dynamic iconic representations during problem solving, it was identified how frequently kinematics concepts which change over time were explicitly mentioned in the students' verbalizations and depicted or drawn in their written problem-solving attempts. The frequencies are shown in Table 2. There were no significant differences between groups. In group S+DIR, only two verbalizations and four depictions/drawings of only three students gave rise to the interpretation that these students had developed mental representations which did not only comprise dynamic aspects of kinematics concepts but also iconic aspects.

Table 2. The means (M) and standard deviations (SD) of how frequently the students referred to kinematics concepts that change over time.

	Simulation environment	
Source of information	S	S+DIR
Verbalizations	M = 17.8 (SD = 9.2)	M = 13.7 (SD = 8.4)
Written problem-solving attempts	M = 4.8 (SD = 7.1)	M = 5.8 (SD = 5.9)

Conclusion

In two experimental studies we investigated whether students' understanding of line graphs in kinematics can be improved by means of dynamic iconic representations. These representations were designed to help students in mentally bridging the gap between motion phenomena and abstract line graphs. In the first study, however, the students had severe difficulties in comprehending the information encoded in dynamic iconic representations. This finding was underpinned by the second study, in which almost no sign was found of students having internalized the dynamic and iconic aspects of the employed representations.

It is well possible that learning with the dynamic iconic representations placed too many cognitive demands on the students within too short a period of time. However, because difficulties in learning from dynamic representations have been observed in many recent studies which investigated the acquisition of knowledge in different application domains, it is rather implausible that limited learning time is the only reason for these difficulties. In various studies it has been observed that many students process dynamic representations only superficially (e.g., Lowe, 2003; Ploetzner, Bodemer, & Neudert, in press; Yeo et al., 2004). A growing body of research indicates that the students may have no means at hand to adequately process dynamic representations. The principled design of external representations (e.g., Clark & Mayer, 2003) seems to be only one side of the coin. The other side of the coin seems to consist of the external and internal learning activities which the students actually apply to the external representations. One example in which the design of external representations has been successfully complemented with the design of learning strategies is learning from text. A second example is learning from hypertext.

What makes us assume that students do not need to learn how to learn from dynamic representations? For instance, in order to improve learning from dynamic representations, students possibly need to learn how to identify and analyse relevant components of these representations. Students might also need to learn how to relate the information presented in dynamic representations to other sources of information such as instructional texts. Possibly, in the years to come, we may not only need to develop guidelines for the external design of dynamic representations, but also to conceptualise learning strategies made up of external as well as internal learning activities, which we can teach to students and which help them to successfully process the information presented in the external representations.

References

Ainsworth, S. (1999). The functions of multiple representations. *Computers and Education*, *33*, 131-152.

Berg, C. A., & Smith, P. (1994). Assessing students' abilities to construct and interpret line graphs: Disparities between multiple-choice and free-response instruments. *Science Education*, *78*, 527-554.

Bétrancourt, M., & Tversky, B. (2000). Effect of computer animation on users' performance: A review. *Le Travail Humain*, *63*(4), 311-329.

Chi, M. T. H. (1997). Quantifying qualitative analyses of verbal data: A practical guide. *The Journal of the Learning Sciences*, *6*(3), 271-315.

Clark, R. C., & Mayer, R. (2003). *E-learning and the science of instruction*. San Francisco, CA: Pfeiffer.

de Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research*, *68*(2), 179-201.

Hake, R. R. (1998). Interactive engagement versus traditional methods: A six-thousand-students-survey of mechanics test data for introductory physics courses. *American Journal of Physics*, *66*, 67-74.

Heuer, D. (2002). *PAKMA 2002 – Physik interaktiv simulieren, messen, reproduzieren, modellieren und analysieren* [PAKMA 2002 – Interactive simulation, measurement, reproduction, modelling and analysis in physics; CD-ROM]. Hannover: Schroedel Verlag.

Leinhardt, G., Zaslavsky, O., & Stein, M. K. (1990). Functions, graphs, and graphing: Tasks, learning, and teaching. *Review of Educational Research*, *60*, 1-64.

Lowe, R. K. (2003). Animation and learning: Selective processing of information in dynamic graphics. *Learning and Instruction*, *13*(2), 157-176.

McDermott, L. C., Rosenquist, M. L., & van Zee, E. H. (1987). Student difficulties in connecting graphs and physics: Examples from kinematics. *American Journal of Physics*, *55*, 503-513.

Ploetzner, R., Bodemer, D., & Neudert, S. (in press). Successful and less successful use of dynamic visualisations in instructional texts. In R. K. Lowe & W. Schnotz (Eds.), *Learning with animation - Research and implications for design*. New York, NY: Cambridge University Press.

Ploetzner, R., & Lowe, R. K. (Eds.). (2004). Special issue on dynamic visualisations and learning. *Learning and Instruction*, *14*(3), 235-240.

Raven, J. C. (1980). *RAVEN-Matrizen-Test – Advanced progressive matrices*. Weinheim: Beltz Verlag.

Reif, F., & Allen, S. (1992). Cognition for interpreting scientific concepts: A study of acceleration. *Cognition and Instruction*, *9*(1), 1-44.

Scanlon, E. (1998). How beginning students use graphs of motion. In M. W. van Someren, P. Reimann, H. P. A. Boshuizen & T. de Jong (Eds.), *Learning with multiple representations* (pp. 67-86). Amsterdam: Pergamon Press.

Yeo, S., Loss, R., Zadnik, M., Harrsion, A., & Treagust, D. (2004). What do students really learn from interactive multimedia? A physics case study. *American Journal of Physics*, *72*(10), 1351-1358.

Acknowledgments