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Students' difficulties in learning from dynamic visualisations and how they may be overcome

Rolf Ploetzner [a,*], Stefan Lippitsch [a], Matthias Galmbacher [b], Dieter Heuer [b], Sarah Scherrer [a]

[a] University of Education, Institute of Media in Education, Kunzenweg 21, D-79117 Freiburg, Germany
[b] University of Wuerzburg, Department of Physics, Am Hubland, D-97074 Wuerzburg, Germany

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ABSTRACT

We investigated whether students' understanding of line graphs can be improved by means of dynamic visualisations. The visualisations were designed to help students relate motion phenomena and line graphs to one another. In an initial study three groups were formed: the first group learned on the basis of simulated motion phenomena and dynamic line graphs; the second group additionally had dynamic iconic representations available to them; the third group was also presented with dynamic stamp diagrams. Contrary to our expectations, students were not able to make use of the visualisations in order to improve their understanding of line graphs. We hypothesised that students did not receive sufficient support in comprehending the visualisations. In a second study two groups were investigated. While the first group learned on the basis of simulated motion phenomena and dynamic line graphs, the second group additionally had dynamic iconic representations as well as dynamic stamp diagrams available to them. It was possible for the students in both groups to ask questions and to receive assistance from a teacher as well as from peers while learning from the visualisations. The results demonstrate that the pedagogical measures enabled the students to successfully make use of dynamic visualisations.

1. Introduction

1.1. Dynamic and interactive representations in physics

Physics education aims at helping students to view physics as a consistent system of concepts and principles related to the physical world. For the past two decades, however, research on physics education has demonstrated that many students face severe difficulties in learning physics. Even after participating in physics courses for several years, many students view physics as a fragmentary collection of phenomena, algebraic formulas, and problem-solving procedures (e.g., Anzai & Yokoyama, 1984; Reif & Heller, 1982). Research on physics education has identified various factors which contribute to the difficulty of learning physics. While some of these factors are related to the students, such as the students' preconceptions about physics (e.g., Clement, 1982; Halloun and Hestenes, 1985a, 1985b; for a bibliography see Duit, 2004) as well as the students' beliefs about what it means to understand physics (e.g., Elby, 2001), other factors are related to the way in which physics is taught (e.g., Linn, Davis, & Bell, 2004; Ploetzner & VanLehn, 1997; White, 1983, 1993).

When teaching physics, educators frequently employ external representations, reaching from textual and pictorial descriptions of physical phenomena to symbolic and graphical representations of physics concepts and principles. Different external representations may single out different aspects of a physical phenomenon or a physics concept, describe aspects of a physical phenomenon 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 (cf. Ainsworth, 1999, 2006; Johnson & Lesh, 2003). Computers offer the additional opportunity to educators to take advantage of dynamic representations in order to represent physical phenomena as well as physics concepts that change in time and space (e.g., Ainsworth & VanLabeke, 2004).

While educators employ external representations to improve students' understanding, such representations also place specific demands on students (for a collection of papers see Ploetzner & Lowe, 2004). For instance, students need to understand (1) how information is encoded in each single representation, (2) how each representation is related to the physical world, and (3) how information in one representation can be related to or transformed into information in another representation (cf. Ainsworth, 1999, 2006; Ainsworth, Bibby, & Wood, 1998; Anzai, 1991; Johnson & Lesh, 2003).

Dynamic representations can provide visualisations of time-dependent phenomena, concepts and principles. At the same time,

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* Corresponding author. Tel.: +49 761 682 900; fax: +49 761 682 922.
E-mail address: rolf.ploetzner@ph-freiburg.de (R. Ploetzner).

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however, they require students to process large amounts of continuously changing information and to direct their attention simultaneously to different regions of the computer screen (e.g., Lowe, 1999, 2003, 2004). If external representations are not only dynamic but also interactive, they may encourage discovery learning processes (e.g., de Jong & van Joolingen, 1998; Rieber, 1994). However, the mere provision of interactivity does not guarantee its effective use. Successful learning with interactive representations demands from students that they carefully prepare, execute, and evaluate their interactions (e.g., de Jong & van Joolingen, 1998; Ebner & Holzinger, 2007).

While it is frequently taken for granted that the use of different external representations in computer-based learning environments is beneficial to learning, a growing body of educational and psychological research indicates that the combination of various external representations might not only not improve, but even impede learning. Very often, the demands placed on students due to the use of different external representations seem to overburden the students' cognitive capacities (e.g., Sweller, 2005; Sweller & Chandler, 1994; Sweller, van Merriënboer, & Paas, 1998). For instance, students with little prior knowledge in the respective subject matter can have severe difficulties in systematically relating different external representations to each other (e.g., Ainsworth et al., 1998; Anzai, 1991), adequately processing dynamic representations (e.g., Lowe, 1999, 2003, 2004), and appropriately controlling interactive representations (e.g., de Jong & van Joolingen, 1998; Yeo, Loss, Zadnik, Harrsion, & Treagust, 2004). As a consequence, these students fail to construct coherent mental representations.

One notorious problem in physics education is the difficulty students have understanding line graphs (e.g., Beichner, 1994; Bell & Janvier, 1981; Berg & Smith, 1994; Scanlon, 1998). In this paper we investigate whether students' understanding of line graphs in kinematics can be improved by means of dynamic visualisations. In the following, we summarise empirical findings concerning students' difficulties in understanding line graphs in kinematics. Next, we describe a computerised environment in which motion phenomena are simulated. We then explore how students' understanding of line graphs in kinematics can be improved by enriching simulated motion phenomena with so-called dynamic iconic representations of kinematics concepts. Thereafter, two experimental studies are described in which students learned physics while having different dynamic visualisations available to them. We conclude with a discussion of the empirical observations and a proposal for future lines of research.

1.2. Enriching interactive simulations with dynamic iconic representations

In kinematics, line graphs visualise the functional relationship between time and kinematics concepts such as an object's position, velocity, and acceleration. Fig. 1 shows a time-position graph. At least two abilities are related to any understanding of line graphs in kinematics. First, the ability to construct a line graph that appropriately represents an object's motion. Such a construction may start from observing an object's motion or from processing a verbal, visual or mathematical description of an object's motion. Second, the ability to interpret a line graph, i.e., to formulate an appropriate verbal, visual or mathematical description of the motion underlying the line graph.

In physics textbooks, line graphs are often developed in three steps. In the first step, an object's motion is textually and pictorially described. In the second step, the values of a kinematics concept at various points in time are presented in a table. In the third step, these values as well as their interpolation are visualised in a coordinate plane, resulting in a line graph.

Research on physics education has repeatedly demonstrated that students often have severe difficulties in understanding line graphs (e.g., Beichner, 1994; Bell & Janvier, 1981; Berg & Smith, 1994; Scanlon, 1998). These difficulties apply to the construction of line graphs as well as to the interpretation of line graphs (for a recent collection of papers on graph comprehension see Barker-Plummer, Cox, & Swoboda, 2006). 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 concepts the graphs visualise (e.g., McDermott, Rosenquist, & van Zee, 1987). Even after participating in several physics courses, many students are hardly able to relate

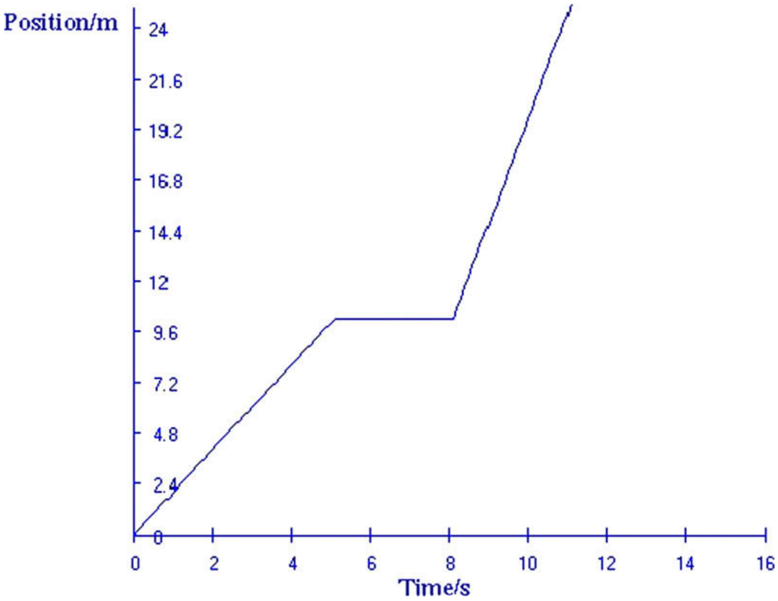

Fig. 1. A time-position graph: the first five seconds the object moves with constant velocity, the next three seconds it remains at rest, thereafter it moves again with constant and – in comparison to the first five seconds – increased velocity.

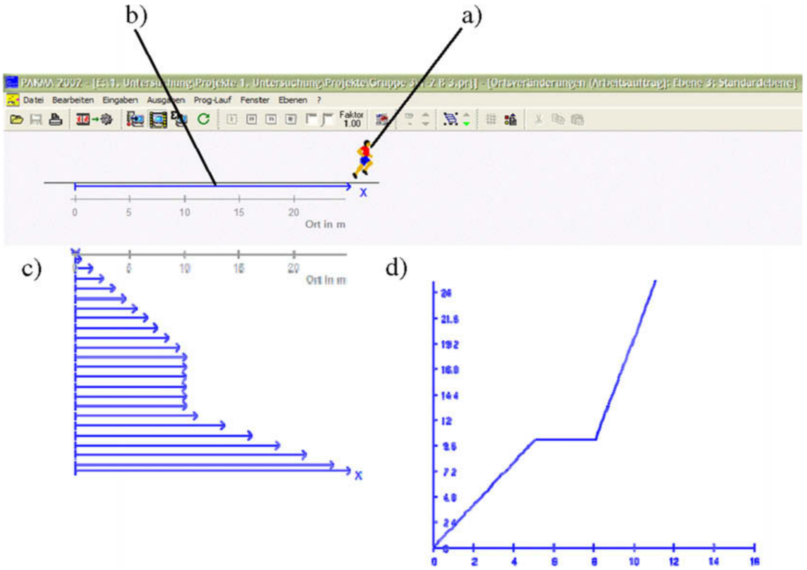

Fig. 2. The user-interface of PAKMA: (a) a simulated motion phenomenon (the motion of a runner), (b) a dynamic iconic representation (a vector representing the distance covered by the runner), (c) a stamp diagram (a set of vectors representing the distances covered by the runner at various points in time), and (d) a line graph visualising the distance covered by the runner over time.

motion phenomena on the one hand and graphical representations of physics concepts on the other.

Is it possible to improve students' understanding of line graphs by means of dynamic visualisations? In order to investigate this question, we took advantage of the simulation program PAKMA (Heuer, 2002). PAKMA provides a computerised environment in which motion phenomena can be interactively simulated. The simulation can be started and stopped at any time. It can be run continuously or frame by frame. In comparison to textbooks, PAKMA offers the opportunity to visualise how different external representations change in time. In order to help students understand how motion phenomena and line graphs are related to each other, four different types of dynamic visualisations are employed in PAKMA (see Fig. 2): (a) simulations of motion phenomena, (b) dynamic iconic representations, (c) stamp diagrams, and (d) line graphs.

While physics textbooks illustrate motion phenomena using static pictures, PAKMA visualises them dynamically. Dynamic iconic representations correspond to vector representations of kinematics concepts such as position, distance, velocity and acceleration. These representations are iconic because they visually represent the vectors' main structural components: their directions and their magnitudes. While physics textbooks depict vectors with static pictures, PAKMA dynamically visualises how vectors change in time. Furthermore, in PAKMA dynamic iconic representations are superimposed on visualisations of motion phenomena. Stamp diagrams result from stamping dynamic iconic representations of vectors onto a coordinate plane at defined points in time. To our knowledge, stamp diagrams are not part of physics textbooks. Line graphs result from stamp diagrams by interpolating the vectors' heads. Depending on whether a horizontal or vertical motion phenomenon is simulated, the resulting graph needs to be subsequently rotated (see Fig. 2). Yet again, while physics textbooks illustrate line graphs by means of static pictures, PAKMA visualises them dynamically.

In an experimental study we investigated whether students' understanding of line graphs in kinematics improves depending on the visualisations made available to them. We distinguished three conditions. In the first – control – condition (abbreviated Group S), only simulated motion phenomena and line graphs were made available to the students. In this condition, the visualisations used in physics textbooks and in PAKMA resemble each other. Unlike physics textbooks, however, PAKMA provides dynamic visualisations. This could help students to understand line graphs; then due to the spatial and, especially, temporal contiguity of both visualisations, students may be able to more successfully relate an object's motion to a line graph.

Still, simulated motion phenomena do not comprise any visible components that correspond to components visible in line graphs. Dynamic iconic representations visually represent the directions and magnitudes of those physics concepts underlying the simulated motion phenomena. Therefore, in the second condition (abbreviated Group S+DIR), students not only had simulated motion phenomena and line graphs made available to them, but also dynamic iconic representations, which were superimposed on motion phenomena. Because visible changes in the dynamic iconic representations, for instance changes in magnitude, correspond directly to visible changes in the line graphs, these visualisations could further help students to relate motion phenomena to line graphs.

Because for many students it might still be difficult to notice how dynamic iconic representations and line graphs are related to each other, we introduced stamp diagrams in the third condition (abbreviated Group S+DIR+Stamps). Stamp diagrams form a representation inbetween dynamic iconic representations and line graphs. Dynamic iconic representations of vectors are stamped onto a coordinate plane at defined points in time. Stamp diagrams are made up of collections of dynamic iconic representations on the one hand and almost resemble line graphs on the other.

Ainsworth (1999, 2006) proposes that external representations can function by constraining and guiding the interpretation of other external representations. The dynamic visualisations employed in PAKMA exemplify this function: dynamic iconic representations and stamp diagrams were introduced to help students to interpret and understand line graphs. Accordingly, we hypothesised that compared to the mere availability of motion phenomena and line graphs, the availability of dynamic iconic representations would make it easier for students to relate motion phenomena and line graphs to each other. We further hypothesised that the additional availability of stamp diagrams would help students even more to relate motion phenomena and line graphs to each other.

2. Study 1

2.1. Method

2.1.1. Design

As an independent variable, a factor named "simulation environment" has been varied. Three different simulation environments have been set up by means of PAKMA. In the first environment (provided to Group S), motion phenomena were interactively simulated and line graphs were dynamically displayed. In the second environment (provided to Group S+DIR), dynamic iconic representations of vectors were additionally superimposed on the simulations of the motion phenomena. In the third environment (provided to Group S+DIR+Stamps), dynamic stamp diagrams were also displayed.

2.1.2. Participants

Overall, 111 eleventh graders volunteered for the study, 39 in Group S, 33 in Group S+DIR, and 39 in Group S+DIR+Stamps. The students were between 16 and 17 years old. At the time the study took place, the students were at the beginning of class eleven. They had attended introductory classes on the concepts position and velocity, but not on the concepts acceleration and force. While 54 students were girls, 57 students were boys. Girls and boys were distributed approximately equally across the different groups.

2.1.3. Learning material

For each group investigated, the learning material was made up of eight physics projects progressing from the easier concepts to the more difficult. The first two projects were on position and time-position graphs, the next two projects were on velocity and time-velocity graphs, the following two projects were on acceleration and time-acceleration graphs, and the last two projects were on force and time-force graphs. Each project was made up of two components: 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, the students had to answer various questions 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. Students were asked to write down their answers to the questions on the worksheet.

In order not to overburden the students' cognitive capacities, the different dynamic visualisations were introduced to the students step by step in each physics project. Fig. 3 exemplifies the progression through the different visualisations with respect to Group S+DIR+Stamps. Initially, the students were asked to start with a display of a simulated motion phenomenon as well as a dynamic iconic representation (see Fig. 3a). Thereafter, the students were requested to proceed with the display of the stamp diagram (see Fig. 3b). Finally, the students were asked to additionally plot the line graph (see Fig. 3c).

2.1.4. Procedure

Initially, all students took a pre-test to determine their prior knowledge in kinematics as well as their visual-spatial abilities (advanced progressive matrices, Raven, 1980). By means of 14 multiple-choice questions the pre-test in kinematics assessed the students' ability to interpret time-position, time-velocity, time-acceleration, and time-force graphs. Next, the students worked individually on an example physics project in order to learn how to run the simulation environment. Thereafter, the students worked individually on the eight physics projects described above. The learning time for each student was limited to 150 min. Finally, all students worked on a post-test in kinematics, which was an extended version of the pre-test. In 30 multiple-choice questions and eight open questions the post-test assessed the students' ability to interpret as well as to construct time-position, time-velocity, time-acceleration, and time-force graphs.

2.1.5. Hypotheses

Because the students had attended introductory classes on the kinematics concepts position and velocity, we expected them to achieve higher test scores in the pre-test with respect to time-position and time-velocity graphs than with respect to time-acceleration and time-force graphs.

With respect to the availability of dynamic visualisations, we expected that the availability of dynamic iconic representations superimposed on motion phenomena would result in larger learning gains from the pre-test to the post-test than the mere availability of simulated motion phenomena and line graphs would provide. Because stamp diagrams aim at helping students to relate motion phenomena and line graphs even more successfully to each other, we expected that the additional availability of stamp diagrams would result in the largest learning gains from the pre-test to the post-test.

However, we were also aware of the fact that successful learning with the simulation program PAKMA demands the thorough processing of visual and spatial information (cf. Trickett & Trafton, 2006, 2007). Therefore, we expected that students with high visual-spatial abilities would benefit more from the dynamic visualisations than students with low visual-spatial abilities.

2.2. Results

2.2.1. Prior knowledge

The means, relative solution frequencies as well as the standard deviations in the pre-test are shown in Table 1. There are no significant differences in the pre-test scores between groups. As expected, the students were significantly more successful on test items addressing time-position and time-velocity graphs than on test items addressing time-acceleration and time-force graphs ($F(1,110) = 794.1$, $p < .001$).

2.2.2. Learning performance

The means, relative solution frequencies as well as the standard deviations in the post-test are shown in Table 2. In order to analyse the students' learning performance statistically, we computed the students' relative learning gain (cf. Hake, 1998). This puts the potential learning gain (i.e., 100 – Pre-test score) and the actually observable learning gain (i.e., Post-test score – Pre-test score) into relation:

$$\text{Relative learning gain} = [(\text{Post-test score} - \text{Pre-test score})/(100 - \text{Pre-test score})] \times 100$$

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. While Fig. 4 shows the relative learning gains with respect to the interpretation and construction of time-position and time-velocity graphs, Fig. 5 shows the relative learning gains with respect to the interpretation and construction of time-acceleration and time-force graphs. The results of a multivariate and univariate two-way analysis of variance are summarised in Table 3.

Contrary to our expectations, in the multivariate analysis there are no significant differences in learning gains between groups across time-position, time-velocity, time-acceleration, and time-force graphs. In the univariate analysis, there are no significant

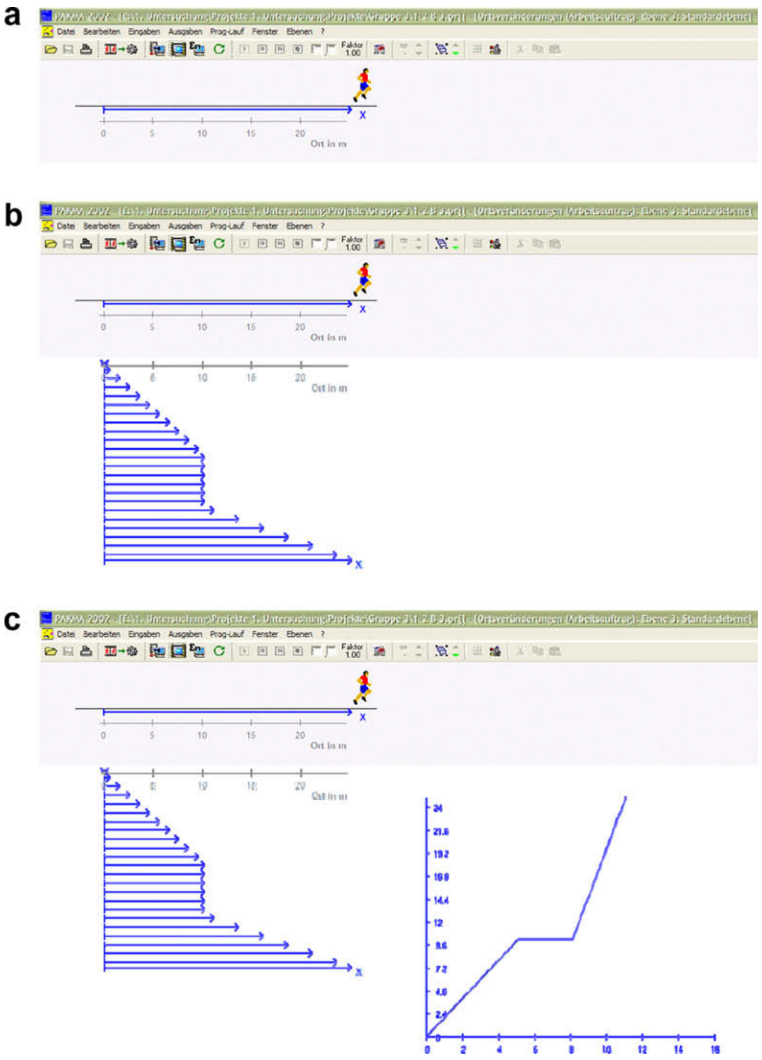

Fig. 3. Displaying the dynamic visualisations step by step: (a) starting with a simulated motion phenomenon and a dynamic iconic representation, (b) adding the stamp diagram, and (c) adding the line graph.

Table 1
The means (*M*), average relative solution frequencies, and standard deviations (SD) in the pre-test

Performance	S			S+DIR			S+DIR+Stamps		
	M		SD	*M*		SD	*M*		SD
Time-position and time-velocity graphs	3.82	(64%)	1.23	3.72	(62%)	1.42	3.89	(65%)	1.18
Time-acceleration and time-force graphs	2.12	(27%)	1.79	2.12	(27%)	1.89	2.48	(31%)	1.83
Across all graphs	5.93	(45%)	2.55	5.84	(44%)	2.79	6.37	(48%)	2.51

Table 2
The means (*M*), average relative solution frequencies, and standard deviations (SD) in the post-test

Performance	S			S+DIR			S+DIR+Stamps		
	M		SD	*M*		SD	*M*		SD
Time-position and time-velocity graphs	11.84	(74%)	2.87	10.96	(69%)	3.48	12.02	(75%)	2.28
Time-acceleration and time-force graphs	9.41	(43%)	5.87	7.45	(34%)	5.23	8.15	(37%)	6.20
Across all graphs	21.25	(58%)	7.79	18.41	(51%)	7.85	20.17	(56%)	7.71

differences in learning gains between groups with respect to time-position and time-velocity graphs, but there are significant differences in learning gains between groups with respect to time-acceleration and time-force graphs. With respect to the factor “simulation environment”, however, these differences are diametrically opposed to our predictions: on average, those students who

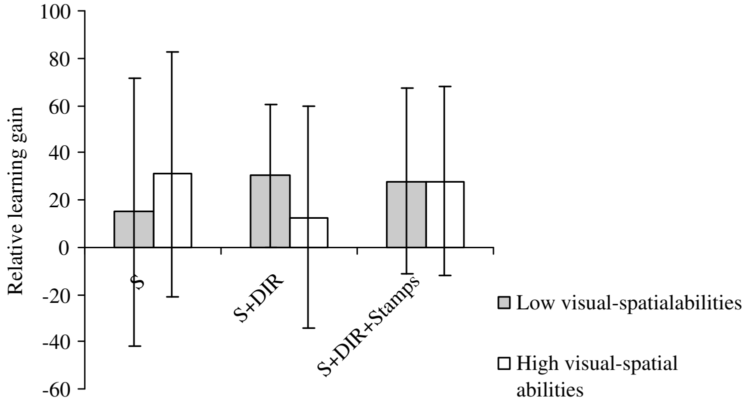

Fig. 4. The relative learning gains with respect to time-position and time-velocity graphs.

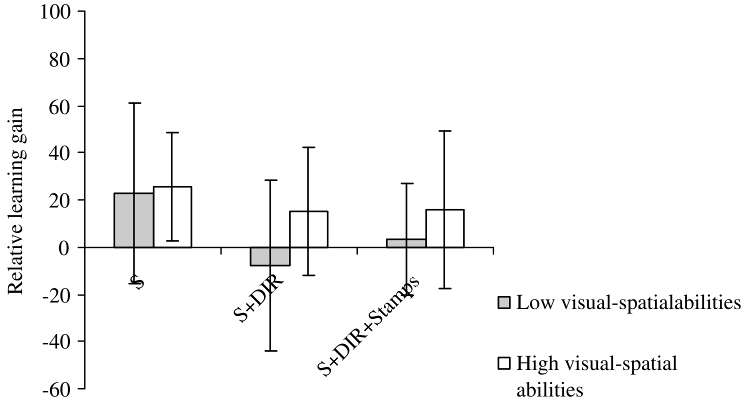

Fig. 5. The relative learning gains with respect to time-acceleration and time-force graphs.

Table 3
The results of a multivariate (Wilks Lambda) and univariate two-way analysis of variance (ANOVA)

Source of variance	Relative learning gain	d*f*	*F*	*p*
Simulation environment	Across all graphs	2, 105	2.70	.072
	Time-position and time-velocity graphs	2, 105	.20	.817
	Time-acceleration and time-force graphs	2, 105	4.19*	.018
Visual-spatial abilities	Across all graphs	1, 105	1.40	.239
	Time-position and time-velocity graphs	1, 105	.00	.947
	Time-acceleration and time-force graphs	1, 105	4.78*	.031
Simulation environment × visual-spatial abilities	Across all graphs	2, 105	.20	.814
	Time-position and time-velocity graphs	2, 105	1.18	.309
	Time-acceleration and time-force graphs	2, 105	.95	.390

$p < .05$.

only had simulated motion phenomena and line graphs available to them displayed higher learning gains than those students who additionally had dynamic iconic representations and stamp diagrams available to them.

Concerning the – post hoc – factor “visual-spatial abilities”, our expectations only held true with respect to time-acceleration and time-force graphs. On average, students with low visual-spatial abilities accomplished significantly smaller learning gains than students with high visual-spatial abilities. This is especially true for those students who had the dynamic iconic representations available to them, but not the stamp diagrams: these students performed even better in the pre-test than they did in the post-test. Nonetheless, the interaction between the factors “simulation environment” and “visual-spatial ability” is statistically insignificant.

2.3. Discussion

We expected that the additional availability of dynamic iconic representations of kinematics concepts would result in larger learning gains than the mere availability of simulated motion phenomena and line graphs would provide. Because stamp diagrams aim at helping students to relate motion phenomena and line graphs even more successfully to one another, we expected that the additional availability of stamp diagrams would result in the largest learning gains. However, taking into account earlier findings in research on learning with dynamic visualisations, we also anticipated that only students with high visual-spatial abilities would successfully learn from the different visualisations.

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 concepts position and velocity (cf. Reif & Allen, 1992; Reif & Heller, 1982), the availability of these representations made no significant difference. However, with respect to the more difficult concepts acceleration and force (cf. Reif & Allen, 1992; Reif & Heller, 1982), the availability of dynamic iconic representations and stamp diagrams hindered learning. This is especially true for students with low visual-spatial abilities. Students with low visual-spatial abilities who learned kinematics with dynamic iconic representations, but without stamp diagrams, even declined in their performance from the pre-test to the post-test. Although stamp diagrams partially compensated for the difficulties which were associated with dynamic iconic representations, they nevertheless did not improve learning beyond the learning gains which were achieved without dynamic iconic representations and stamp diagrams.

Students' learning performance was best when they learned from representations which were close to the representations used in physics textbooks. Although these findings contradict our expectations, they are in line with other findings in research on learning with dynamic visualisations (e.g., Bétrancourt & Tversky, 2000; Lowe, 1999, 2003, 2004; Schnotz, Böckheler, Grzondziel, Gärtner, & Wächter, 1998; Yeo et al., 2004): it is possible that the students were neither able to identify the relevant information in each representation, nor to relate the representations to each other. Perhaps we overburdened the students' cognitive capacities (cf. Holzinger, Kickmeier-Rust, & Albert, 2008): (1) they had to learn two new and difficult kinematics concepts, namely acceleration and force, as well as their graphical representations, (2) on the basis of unknown dynamic visualisations, namely dynamic iconic representations and dynamic stamp diagrams, (3) within a relatively short period of time, and (4) without the opportunity to clarify any questions concerning the physics concepts and the dynamic visualisations. Would students learn more successful when the number of physics concepts is decreased, the time available for learning is increased, and questions can be clarified during learning? In order to evaluate whether this combination of measures improves learning from dynamic iconic representations and dynamic stamp diagrams, we conducted a second study.

3. Study 2

3.1. Method

3.1.1. Design

Two groups were formed, who made use of two different simulation environments. In the first environment (abbreviated S), motion phenomena were interactively simulated and line graphs were dynamically displayed. In the second environment (abbreviated S+DIR+Stamps), additional dynamic iconic representations were superimposed on the motion phenomena and dynamic stamp diagrams were displayed.

3.1.2. Participants

Overall, 24 volunteer tenth graders were randomly assigned to the groups: 12 students were assigned to Group S and 12 students were assigned to Group S+DIR+Stamps. The students were between 15 and 16 years old. At the time the study took place, the students were at the end of class 10. They had attended introductory classes on position and velocity but not on acceleration. While 13 students were girls, 11 students were boys. Girls and boys were distributed approximately equally across the groups.

3.1.3. Learning material

For each group investigated, the learning material comprised 12 physics projects progressing from the easier concepts to the more difficult. The first four projects were on position and time-position graphs, the next four projects were on velocity and time-velocity graphs and the last four projects were on acceleration and time-acceleration graphs. Force and time-force graphs were not included in this study because Study 1 revealed that these concepts are very difficult to the students and we did not want to overburden the students' cognitive capacities again. As in Study 1, each project was made up of two components: a worksheet and a simulation environment.

3.1.4. Procedure

Initially, all students took a pre-test to determine their prior knowledge in kinematics as well as their visual-spatial abilities (advanced progressive matrices, Raven, 1980). By means of 11 multiple-choice questions the pre-test in kinematics assessed the students' ability to interpret time-position and time-velocity graphs. Time-acceleration graphs were not included in the pre-test, because we had no reason to assume that tenth graders possess significant prior knowledge about these graphs. Next, the students worked individually on an example physics project in order to learn how to run the simulation environment.

In both groups, the four projects addressing a certain kinematics concept were processed as follows. A teacher demonstrated step by step the first project to the students. Subsequently, pairs of students worked collaboratively on the second project. Finally, the students worked individually on the third and fourth project. At the end of each project, the teacher recapitulated the essentials of the project in a standardised way by means of a pre-formulated summary. Furthermore, the students could pose questions which were answered by the teacher. To answer the students' questions in a standardised way, the teacher made use of a set of pre-formulated explanations.

With respect to each single concept, learning time was limited to 60 min. Overall, learning time was limited to 180 min. Finally, all students worked on a post-test in kinematics which was an extended version of the pre-test. By means of 30 multiple-choice questions and 36 open questions the post-test assessed the students' ability to interpret as well as to construct time-position, time-velocity, and time-acceleration graphs.

3.1.5. Hypotheses

Because we assume that dynamic iconic representations as well as stamp diagrams make it easier for students to relate motion phenomena and line graphs to each other, we expected that Group S+DIR+Stamps would outperform Group S in the post-test. Because we further assume that dynamic iconic representations are especially beneficial when assessing difficult concepts, we also expected that the more difficult the respective concept became, the higher the degree by which Group S+DIR+Stamps would outperform Group S in the post-test.

3.2. Results

3.2.1. Prior knowledge

The means, relative solution frequencies and standard deviations in the pre-test are shown in Table 4. A multivariate analysis of variance (MANOVA) reveals no significant differences in the pre-test scores between groups on the multivariate level ($F(2,21) < 1$, $p = .96$) as well as on the univariate level ($F(1,22) < 1$, $p = .81$ and $F(1,22) < 1$, $p = .89$).

Table 4
The means (*M*), average relative solution frequencies, and standard deviations (SD) in the pre-test

Performance	S			S+DIR+Stamps		
	M		SD	*M*		SD
Time-position graphs	1.33	(66%)	0.88	1.42	(70%)	0.79
Time-velocity graphs	4.75	(52%)	1.65	4.83	(53%)	1.89
Across all graphs	6.08	(59%)	1.64	6.25	(61%)	2.14

Table 5
The means (*M*), average relative solution frequencies, and standard deviations (SD) in the post-test

Performance	S			S+DIR+Stamps		
	M		SD	*M*		SD
Time-position graphs	11.92	(85%)	1.56	12.58	(90%)	0.99
Time-velocity graphs	15.42	(61%)	3.28	17.08	(68%)	2.10
Time-acceleration graphs	14.83	(47%)	6.25	18.50	(59%)	7.34
Across all graphs	42.17	(64%)	12.04	48.16	(72%)	11.04

3.2.2. Learning performance

The means, relative solution frequencies and standard deviations in the post-test are shown in Table 5. Additionally, the average relative solution frequencies in the post-test are presented in Fig. 6. A multivariate analysis of variance with repeated measurements (MANOVA) reveals that in both groups the students' ability to interpret and construct line graphs increased significantly from the pre-test to the post-test with respect to time-position graphs ($F(1,22) = 5.50$, $p < .05$), as well as with respect to time-velocity graphs ($F(1,22) = 6.29$, $p < .05$). Performance on time-acceleration graphs was not included in this analysis, as it was not assessed in the pre-test. There was no significant relationship between visual-spatial ability and achievement in the post-test ($r = .20$, $p = .33$).

Descriptively, Group S+DIR+Stamps outperformed Group S in the post-test with respect to every single concept. Furthermore, Group S+DIR+Stamps outperformed Group S even more, the more difficult the concept was. A multivariate analysis of variance (MANOVA), however, reveals no significant differences in the post-test scores between groups on the multivariate level ($F(3,20) < 1$, $p = .38$) as well as on the univariate level.

3.3. Discussion

With the second study, we aimed at a primary evaluation of the question whether students learn more successfully from dynamic iconic representations and stamp diagrams, if the students are given more time and support to understand the dynamic visualisations, as well as how they are related to line graphs. Possibly due to small samples, the differences found at the level of descriptive statistics were not confirmed at the level of inferential statistics. Nevertheless, the study indicates that dynamic iconic representations and dynamic stamp diagrams have the potential to improve students' understanding of line graphs. This seems to be especially true when learning difficult concepts and the line graphs related to them.

Furthermore, in the second study visual-spatial abilities had a much weaker influence on learning performance than they had in the first study. This finding might indicate that in the first study students basically had to figure out themselves which information is encoded in the different visualisations and how this information is related to line graphs. While students with high visual-spatial abilities succeeded in doing so, most students with low visual-spatial abilities failed in doing so. In the second study, in contrast, the students received more systematic information about the different visualisations and how they are related to line graphs. Therefore, visual-spatial abilities might not have come into play to the same degree as in the first study.

4. General discussion

There is a growing body of research indicating that students frequently face severe difficulties in learning from interactive and dynamic visualisations, such as interactive simulations (e.g., de Jong & van Joolingen, 1998; Yeo et al., 2004) and animations (e.g., Lowe, 1999, 2003, 2004; Schnotz & Rasch, 2005). Basically, three different approaches can be distinguished to help students overcome these difficulties.

The first approach is the principled design of external representations (for a collection of papers see Mayer, 2005). This approach essentially aims at making the identification and selection, as well as the mental organisation and integration of relevant information, as easy as possible for students. It was demonstrated in many studies that the principled design of external representations facilitates learning. In the last ten years, especially research in the cognitive sciences focused on this approach. We took advantage of this approach in the first study by designing dynamic visualisations in such a way that they constrain and guide students' interpretation of other visualisations (cf. Ainsworth, 1999, 2006). The principled design of external representations, however, does not guarantee learning. Rather, it is only one side of the coin. The other side consists of the learning activities which students actually apply to the learning material.

The second approach is the principled design of pedagogical arrangements (for a collection of papers see Sawyer, 2006). By

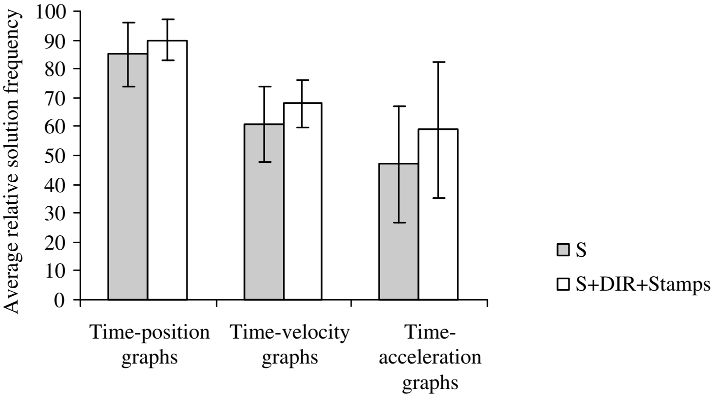

Fig. 6. The average relative solution frequencies in the post-test.

configuring physical and social resources for learning, this approach aims at initiating, sustaining, structuring, supporting and reflecting upon students' learning activities. It has been shown in various studies that the principled design of pedagogical arrangements improves learning from interactive and dynamic visualisations (e.g., Blaschke & Heuer, 2000). In the past, this approach was emphasised in the educational sciences as well as in the educationally oriented sections of sciences such as biology, chemistry and physics. We made use of this approach in the second study by complementing the principled design of dynamic visualisations with pedagogical measures which aimed at initiating and supporting students' processing of these visualisations. The combination of both approaches led to more successful learning than the principled design of dynamic visualisation alone.

The third approach is the principled design of learning strategies. With respect to learning from interactive and dynamic visualisations, this approach has largely been neglected up unto now. Educational and psychological research indicates, however, that many students may have no strategies at hand in order to successfully process interactive and dynamic visualisations. One example in which research on the design of external representations has been successfully complemented with research on the design of learning strategies is learning from text. Numerous principles have been identified on how texts could be designed in order to ease and support students' learning from texts (e.g., Gropper, 1991; Jonassen, 1985). These principles address issues of content as well as issues of structure and the layout of texts. However, no one assumes that texts designed according to these principles ensure students' success in learning from texts. Instead, from the elementary level to the university level, students are taught reading and learning strategies which take into account the specific characteristics of texts. These strategies involve internal learning activities such as previewing, paraphrasing and summarising (e.g., Thomas & Robinson, 1972) as well as external learning activities such as highlighting phrases, taking notes and drawing visualisations (e.g., Leutner & Leupold, 2003). Thus, after many years of education, students have acquired and exercised a number of internal and external strategies which help them to systematically approach especially complex and difficult texts.

What makes us assume that students do not need to learn how to learn from dynamic and interactive visualisations? For instance, in order to improve learning from dynamic and interactive visualisations, students possibly need to learn how to identify relevant components of the visual display, as well as how to relate spatially and temporally separated components to one another (cf. Lowe, 1999, 2003, 2004). Students may also need to learn how to relate the information presented in dynamic and interactive visualisations 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 and interactive representations, but also to conceptualise learning strategies which can be taught to students. These strategies need to empower students to successfully learn from interactive and dynamic visualisations, especially if a pedagogical framework is lacking.

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