Introduction to Newtonian mechanics via two-dimensional dynamics - The effects of a newly developed content structure on German middle school students

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Abstract:

Newtonian mechanics is still among the most difficult topics in the physics' syllabus taught at school. For example, even after completing traditional instruction, students still think that a force is necessary to maintain motion. Therefore, a revised method of instruction is needed that meets students' learning needs.

The aim of the project presented in this article was to develop and evaluate novel teaching units for the introduction to Newtonian mechanics. Rather than changing methodology, the content area itself was restructured innovatively with careful consideration of the most common preconceptions. Based on diSessa's notion of conceptual change as the reorganisation of these only loosely connected preconceptions, so-called p-prims (diSessa, 1993, 2008), the strategy pursued was aimed at triggering the activation of appropriate p-prims while avoiding the activation of inappropriate p-prims. For example, to lower the activation priority of the above mentioned notion, a consistent introduction to mechanics via two-dimensional dynamics was chosen.

In the first year of the corresponding study, 10 participating teachers taught their 7th-grade classes in the traditional one-dimensional way. In the following year, the same teachers taught (other) 7th-grade classes using the revised two-dimensional way. Students' knowledge of mechanics, self-concept and interest in physics were assessed. This quasi-experimental field study showed a significant improvement in students' conceptual understanding. Thus the findings of this project suggest that altering the content structure of a particular topic might be an important parameter to improving learning outcomes.

Keywords: Newtonian mechanics, conceptual change, p-prims, quasi-experimental field study

Introduction

We rate Newtonian mechanics as one of the most difficult topics taught at school from an empirical point of view. In the last few decades, physics education has found evidence for students' enormous learning difficulties in mechanics. The consistency of these findings from all over the world is remarkable, and considerable effort has been expended to remedy this situation. Some approaches focus on modelling (e.g. Schecker, 1993), others on interactive engagement (e.g. Docktor & Mestre, 2014), and others on computer tools (e.g. Thornton & Sokoloff, 1990; Thornton, 1996). However, we adopted a different approach: Based on a long tradition in our research groups, we reconstructed the order and the structure in the teaching of the key ideas of Newtonian mechanics. For this we developed a curriculum which uses student ideas as constructive resources to build a conceptual understanding of mechanics. The corresponding study, presented in this paper, aims to answer the research question, if such curricula can enhance middle school students' conceptual understanding of Newtonian mechanics.

The remainder of this paper is divided into six sections: We first outline students' conceptions and conceptual change as the theoretical framework of our project and draw conclusions for our intervention. Subsequently, the methods and the corresponding analysis are described. In conclusion, we present a discussion and outline implications and limitations of our findings.

Theoretical Framework

Students' Conceptions.
A great many studies during the last 30 years have shown that students have preconceived ideas concerning mechanics. Those ideas are frequently referred to as preconceptions or misconceptions, because they are often contradictory to the physical concepts. They are commonly assumed to be among the main reasons for learning difficulties (Champagne, Klopfer, Solomon & Cahn, 1980; Driver & Easley, 1978). This is because, according to widespread theories of learning and teaching, knowledge cannot be merely passed on; rather, it must be constructed individually by interpreting and evaluating the information received against the background of prior knowledge. Learning is therefore an interactive process highly dependent on the students' preconceptions (Jonasson, 1991; Merrill, 1991). Moreover, research has shown that those same preconceptions that students hold before instruction still prevail after instruction, despite students passing traditional tests (Champagne, Klopfer & Anderson, 1980; Gunstone & White, 1981; Hake, 1998; Hestenes & Wells, 1992a, 1992b; Schecker, 1988; Shymansky et al., 1997; Whitaker, 1983; Wilhelm, 2005). Therefore, it seems that traditional instruction on mechanics is ineffective in the majority of cases.

Duit's bibliography of "Students' and Teachers' Conceptions and Science Education" contains over 1300 entries regarding mechanics. For example, Watts and Zylbersztajn (1981) found that 85% of 14-year-old students associated force with motion. In a study by Sadanand and Kess (1990), 82% of senior high-school students referred to the idea that a force is necessary to maintain motion. Tests such as the "Force Concept Inventory" (Hestenes, Wells & Swackhamer, 1992a) or the "Force-Motion Concept Evaluation" (Thornton & Sokoloff, 1997), which were used in many countries with many students, confirm this, also in Germany (Wilhelm, 2005).

Although these preconceived notions can differ slightly from student to student, research has shown that there are many common elements among the vast majority of learners (Driver, Squires, Rushworth & Wood-Robinson, 1994; Duit, 2009; Duit & Treagust, 2012; Müller, Wodzinski & Hopf, 2007). For example, students quite often do not distinguish between speed and velocity[1], and this difficulty is exacerbated by instruction that only looks at one-dimensional movements. Also, acceleration, as the second time derivative of the displacement, is a particularly difficult quantity that is often not separated from velocity by students. Even those students who do make the distinction may consider acceleration to be an increase or decrease in speed, but they will often fail to treat it as a vector, and this is another difficulty exacerbated by analysing only one-dimensional movements. Another very common erroneous idea about motion is that a force is needed to maintain the velocity of an object. This has to be turned into a canonically correct, expert idea that a force is only needed to change the velocity of an object (its speed and/or its direction of movement). Moreover, difficulties differentiating between horizontal and falling motion have been reported by Hast and Howe (2013).

Conceptual Change.
As illustrated in the examples above, teaching and learning physics often requires conceptual change. The cognitive process of conceptual change, originally formulated by Posner, Strike, Hewson & Gertzog (1982), has since been described differently depending on the underlying approach. Chi (2008) poses that to learn scientific concepts, students have to undergo categorical shifts in their ideas. While in the beginning they often believe that force is a property of an (often active) object ('The moving ball has got a force.'), they have to understand that forces are interactions between two or

more objects. Thus the students' ontology of the concept 'force' has to be completely reworked from a property to an interaction.

Some approaches (Vosniadou, Vamvakoussi & Skopeliti, 2008) state that prior knowledge is embedded in a very coherent mental structure. While learning, this mental structure has to be rebuilt. From this point of view conceptual change is understandably an extremely difficult process. Furthermore, a strategy of building on prior ideas for instruction-induced conceptual change is not considered promising. Other approaches, however, state that prior knowledge consists of relatively small cognitive pieces (diSessa, 1993, 2008, 2018). Learning from this point of view is seen as the construction and reorganisation of these previously only loosely-connected ideas into a coherent mental structure. Conceptual change is hence assumed to be feasible, and building on prior ideas for instruction-induced conceptual change seems more promising: "Students have a richness of conceptual resources to draw on. Attend to their ideas and help them build on the best of them". (diSessa, 2008, page 45) These "coherence" and "knowledge in pieces" perspectives are both compared and contrasted by diSessa (2008), whilst the author himself argues "from the pieces side of the fence". He looks "at a critical fault line concerning the structure of naïve ideas as they relate to learning normative scientific ideas. On the one hand, naïve ideas have been described as coherent, systematic or even theory-like - similar enough to scientists' carefully laid out and systematic theories to deserve the same descriptive term. On the other hand, naïve ideas have also been described as many, diverse, 'fragmented' and displaying limited integration and coherence." (diSessa, 2008, page 35)

There are research findings to suggest that student reasoning is often highly sensitive to context, depending in subtle ways on which naïve ideas are activated in particular situations. For example, students sometimes come up with spontaneous explanations when confronted with only slightly modified questions (Hartmann, 2004; Mandl, Gruber & Renkl, 1993; Wiesner, 1993) and their reasoning cannot be accurately described as a coherent and consistent system (Tao & Gunstone, 1999). These findings are better met by diSessa's "Knowledge in Pieces" (KiP) theory than by other theories: "'Little' ideas often appear in some contexts, and not others. Furthermore, as they change to become incorporated into normative systems of knowledge, the contexts in which they operate may change. So, understanding how knowledge depends on context is core to KiP, while it is marginally important or invisible in competing theories." (diSessa, 2018, page 68). In this model, cognitive blocks called phenomenological primitives (p-prims) (diSessa, 1993) are identified, called primitive in the sense that they are minimal abstractions from experience and basic building blocks of cognition. For moving objects, diSessa claims different p-prims, among which we think the following are of utmost importance for the data we present in this paper: "Force as a Mover", "Force as a Deflector" and "Ohm's p-prim". Children experience that shoving an object at rest will result in a motion along the direction of the shove. Generalising this interpretation, many children consequently expect that every object (regardless of its initial velocity) will move in the direction of the force. For many motions, "Force as a Deflector" would be more aligned with Newtonian mechanics than "Force as a Mover" (diSessa, 1993, page 130), as it takes the momentum of the moving object into consideration. "Ohm's p-prim" is based on the everyday experience that there has to be a cause for an action. DiSessa describes this primitive as "an agent that is the locus of an impetus that acts against a resistance to produce some sort of result." (diSessa, 1993, page 126, bold text in the original). Students think, that a continuous force has to be applied to act against a resistance. The greater the resistance, the greater the force needed to maintain a constant movement.

However, the different theoretical perspectives do not provide us with concrete ways for the construction of curricula that aim to foster students' conceptual change. In the classical conceptual change model, Posner, Strike, Hewson, and Gertzog (1982) claim that conceptual change will happen if students are dissatisfied with a prior conception and if the new conception is intelligible, plausible

and fruitful. Different strategies have been discussed in science education research to dissatisfy students with their prior mechanics conceptions, most prominent among them the strategy of producing cognitive conflict. This strategy, however, does not seem to have the desired effects in classrooms. (For an overview see for example Limon, 2001.) A more promising strategy seems to be building on students' conceptions when teaching mechanics (Jung, 1986; Scott, Asoko, & Driver, 1992, Hammer, 2000). To this end, we want to identify contexts that avoid activating "Force as Mover" and enhance "Force as Deflector". We want to construct situations with moving objects where students use the "Force as Deflector" instead of the "Force as Mover" primitive, as it is more helpful. Similarly, we want to construct situations with moving objects where students use "Ohm's p-prim" to explain the change of velocities instead of the velocities themselves.

The idea of our project is to develop a curriculum that uses students' conceptions in a constructive way as resources to build a conceptual understanding of mechanics. In this curriculum, situations are constructed that avoid the activation of inappropriate preconceptions while aiming to activate appropriate preconceptions, from which a scientific understanding can be developed. To this end, we found it necessary to change both, the order in which topics are taught, as well as the way in which they are explained. More details on the construction of the curriculum will be given in the next paragraph.

Intervention

The curriculum used in this study is the result of a long-term project of our research groups lasting more than 40 years, starting with the work of Walter Jung in the 1970s.[2] Numerous cycles of design, implementation, evaluation and redesign have been conducted during the last decades in our groups (e.g. Jung, Reul & Schwedes, 1977; Jung, 1980; Wodzinski & Wiesner, 1994a; Wodzinski & Wiesner, 1994b; Jung, Wiesner & Engelhardt, 1981; Spill & Wiesner, 1988) to fine tune the underlying ideas for teaching mechanics in a dynamical and two-dimensional approach to middle school students. We consider the project presented in this article to be the next step within this research tradition. Here we focus on a quasi-experimental field study to address the effects of the intervention. Additionally, our aim was to develop teaching material for use in real grade seven classroom settings.

Curriculum Design.
We now turn to elaborating how diSessa's concept of p-prims informed the creation of our two-dimensional and dynamical (2DD) approach to mechanics:

Introduction via dynamical mechanics. Connecting to "Ohm's p-prim", students already accept that "nothing comes from nothing". As they believe that there has to be a cause for an action, they can be convinced easily that there has to be a cause for a change. In particular, many students believe that the greater the force exerted on an object, the greater its velocity in that direction. This idea can be redirected to argue that the greater the force exerted on an object, the greater its change in velocity in that direction. We argue that whenever a change in an object's velocity is observed, an unbalanced force is exerted on it and that whenever an unbalanced force is exerted on an object, a change in its velocity can be observed. Thus "Ohm's p-prim" can be used to explain the change of velocities instead of the velocities themselves. Forces are introduced as describing the impact of one body on another body. To give evidence for this, teachers use an experiment in which a moving ball is hit by another body perpendicular to its velocity. This is exactly the experiment which triggers the use of "Force as Deflector" rather than "Force as Mover" (diSessa, 1993). It is performed with heavy steel balls, so that friction only plays a minor role. Stroboscopic images and slow-motion videos are used to make the process observable (Figure 1).
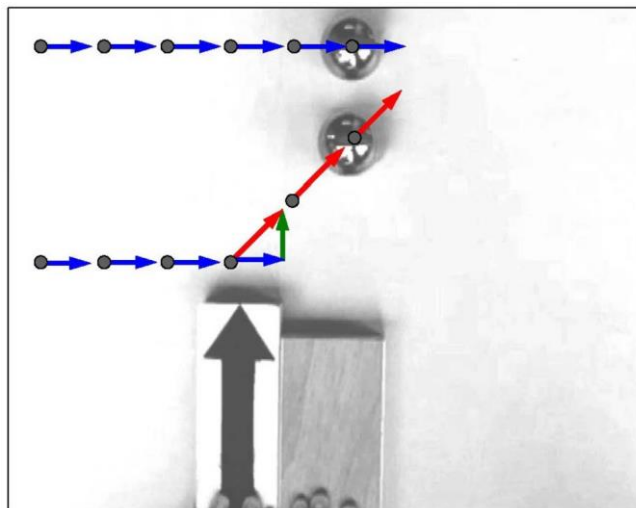
Figure 1. Stroboscopic Image: The combination of the initial velocity (blue) and the additional velocity (green), received while a force is applied on the lower marble, leads to the final velocity (red).

Introduction via two-dimensional mechanics. As discussed above, starting the curriculum by analysing one-dimensional motions seems to hinder the development of conceptual understanding of mechanics. Hence, we start the curriculum by analysing two-dimensional motions. As a tool, arrows are introduced to represent velocity and force.[3] Also the "additional velocity" $\Delta\vec{v}$ is introduced as an independent physical quantity. This quantity replaces "acceleration", which as a second derivative (change of change of position over time) is much harder to conceptualise. We argue that an "initial velocity" is being changed. This can be symbolised by attaching the arrow of the "additional velocity" to obtain the "final velocity" of an object. Formulating dependences between "additional velocity" $\Delta\vec{v}$, force $\vec{F}$, mass m and duration Δt, Newton's second law is obtained as $\vec{F} \cdot \Delta t = m \cdot \Delta\vec{v}$.

Additionally, to prevent difficulties with the differentiation between horizontal and falling motions (cf. Hast & Howe, 2013), only horizontal motions are used in the curriculum until students have develop a good understanding of Newton's second law.

Curriculum Evaluation.
Even though a dynamical, and in particular a two-dimensional approach has already been suggested by some in the field (Jung, Reul & Schwedes, 1977; Jung, 1980; Watts & Zylbersztajn, 1981), this approach has so far lacked consistent implementation and, moreover, empirical evaluation in large-scale analysis. Therefore, we planned a comparative study in 7th-grade classrooms was planned to contrast the learning outcomes of the traditional Bavarian teaching sequence (control group CG) against the alternative curriculum following the two-dimensional and dynamical (2DD) content structure (experimental group EG).

The traditional Bavarian teaching sequence on the one hand (Table 1, left side) starts with the introduction of speed and acceleration in one dimension. Forces are introduced as observable only by their effects (deformation of objects, changing speed of movement, or changing direction of movement), which depend on the magnitude, direction, and points of application of the forces. The discussion of Newton's First Law is followed by the discussion of Newton's Second Law in the form $F = m \cdot a$. A typical experiment involves carts moving on a level track (force and velocity in the same or opposite direction). For this sequence, a lot of teaching materials are available in the commonly used student textbooks.

The 2DD content structure on the other hand (Table 1, right side) starts discussing two-dimensional motions from the beginning and focuses on velocity as a two-dimensional vector quantity. Forces are

introduced as describing the impact of one body on another body, resulting in a change in its initial velocity as it receives an additional velocity $\Delta \vec{v}$. Newton's second law is introduced using the equation $\vec{F} \cdot \Delta t = m \cdot \Delta \vec{v}$, from which Newton's first law is deduced.[4] A typical experiment would involve moving marbles in a plane (force and velocity in different directions). For this teaching sequence, teaching materials, including a 40-page student textbook, were developed (Hopf, Wilhelm, Walther, Tobias & Wiesner, 2011).

Table 1. Overview of the traditional teaching sequence compared to the 2DD content structure.

traditional teaching sequence (control group, CG)	2DD content structure (experimental group, EG)
speed as v = Δs/Δt	discussion of 2dim strobe pictures
acceleration as a = Δv/Δt	velocity as a 2dim vector quantity (speed and direction are both part of the definition)
s-t, v-t, and a-t graphs	additional velocity $\Delta \vec{v}$ as consequence of an exerted force
forces as defined by magnitude, direction and point of application, and equilibrium of forces	proportional reasoning involving force, time, mass and additional velocity $\Delta \vec{v}$
Newton's first law	Newton's second law as $\vec{F} \cdot \Delta t = m \cdot \Delta \vec{v}$
Newton's second law as F=m·a	reasoning with $\vec{F} \cdot \Delta t = m \cdot \Delta \vec{v}$
calculations with F=m·a	Newton's first law
Further topics such as: Newton's third law different kinds of forces force addition and decomposition	Further topics such as: Newton's third law different kinds of forces force addition

Research Questions and Hypothesis.

The effects of the intervention were assessed contrasting the learning outcomes of the traditional Bavarian teaching sequence (CG) with the alternative curriculum following the 2DD content structure (EG). Our research question was: Does a curriculum, which constructively uses students' conceptions as resources to build on, enhance middle school students' conceptual understanding of Newtonian mechanics, while interest and self-concept are not affected?

We formulated the following hypothesis: "Teaching a curriculum which uses students' conceptions as resources results in a better conceptual understanding of mechanics, while interest and self-concept are not affected."

Methods

Participants.

We decided to do this research in regular classrooms to see the effects of the new curriculum acted out under realistic conditions in a field study. 10 teachers volunteered to participate in the study. Those teachers were randomly recruited at a large professional development workshop in Munich in 2007. Every teacher took part in the study for two consecutive school years, participating in the control group (CG) in the first year and participating in the experimental group (EG) in the following

year. So for all (randomly selected) classes in CG, there are again (randomly selected) classes from the same school, only from the next year's cohort of students. In that way we assumed the groups are comparable in background variables such as previous knowledge, interest, self-concept, socioeconomic status, religious and immigration background. We did not check the groups for all those variables, to keep the testing times as short as possible, instead focusing on cognitive abilities, previous knowledge, interest and self-concept.

The control group consisted of 14 classes (358 students); the experimental group of 13 classes (370 students). Since from the 728 students in both groups, only those who completed the whole set of tests and questionnaires were included in the statistical analysis, we had to sort out the data from 207 students. So, for the statistical analysis, the control group comprised N = 266 valid students, the experimental group N = 255 valid students.

Experimental Design.
In summer 2008, the participating teachers taught their 7th-grade classes according to the traditional Bavarian teaching sequence (CG). Followed by, in summer 2009 the same teachers taught (other) 7th-grade classes using the alternative curriculum according to the 2DD content structure (EG), they had received the teaching materials during a half-day CPD-seminar in spring 2009. This way, even though the same teachers taught both courses (CG and EG) in subsequent school years, they were unbiased by the new ideas during the first year (CG) and only learned about those ideas during the second year (EG). Apart from the teaching materials, no additional instruction was given to teachers during the CPD-seminar regarding implementing the curriculum – it was left up to the teachers to think for themselves how to best utilise the teaching materials after the workshop. Once the teachers were back in their own individual grade seven classes at their schools, they autonomously enacted the curriculum during the ongoing term. The reason for this was to make sure, that their way of teaching was – apart from using different curriculums in CG and EG - as constant as possible in both conditions. (Spatz, Wilhelm, Hopf, Waltner & Wiesner, 2019)

Both groups were taught over a period of up to 20 lessons according to the syllabus, during which the teachers kept a diary about their courses (CG: M=18,1 days; SD=3.9 days; EG: M=16.6 days; SD=3.0 days).

Instruments.
Taking the age of the assessed students into account, it did not seem appropriate to use standard knowledge tests developed such as FCI or FMCE. Instead, a new knowledge test consisting of 13 items was constructed (including items from other standard tests such as the FCI[5]). These items were correlated in the post-test with Cronbach's alpha of 0.6. Additionally, we focused on constructing this test to be fair to students taught with the traditional Bavarian teaching sequence as well for those taught with alternative curriculum following the 2DD content structure. Students' interest was assessed with a PISA-based questionnaire and their self-concept was assessed with a questionnaire by Helmke (1992). Both were highly correlated in the pre- as well as in post-test (Cronbach's alpha for the items on interest being 0.8 and on self-concept being 0.9). In addition, a scale of a German cognitive abilities test (Heller & Perleth, 2000) was used to control for the possible different learning preconditions in both groups. Those items were also correlated with a high Cronbach's alpha of 0.7 (Table 2). All tests and questionnaires were given as pre-, post- and follow-up-tests.

Table 2. Overview of the scales used for the statistical analysis.

Scale	Item Example	Number of Items	Reliability $\alpha_{Cronbach}$	Origin
knowledge of mechanics	A truck has a breakdown and is being pushed to a garage by a car.	13	0.6	own items and FCI

	When this car accelerates to a certain speed, which of the following statements about the forces applied is correct? …			
interest	In my physics class I learn new things that are important to me.	5	0.8	own items and PISA 2000
self-concept	I will never really understand physics.	8	0.9	Helmke 1992
cognitive-abilities		15	0.7	Heller & Perleth 2000

Analysis

Descriptive Data Analysis.

A primary analysis of the distribution of boys and girls in the CG and EG was performed and it was found that there was more than a random deviation, which has to be considered in the following analysis ($\chi^2(1) = 7{:}99$; p = .005). In the performance on the cognitive abilities test, the two groups differed only slightly, (entire sample: M=12.44, SD=2.39; CG: M=12.22, SD=2.52; EG: M=12.59; SD=2.25; $t_{(df=510)}$ = 1.76; p = .080). However, with p ≤ .10, this difference is significant by trend, and we cannot completely exclude the assumption of a more than random deviation between the two groups on this scale. Therefore, this finding will be considered in the following analysis as well.

Analysis of conceptual understanding of mechanics. Regarding students' knowledge on the subject matter, no significant differences between the two groups were measured in the pre-test (M=2.92, SD=1.36 in the whole sample; CG: M=2.93, SD=1.38; EG: M=2.90, SD=1.33). After the course, students of the CG reached a mean of M=4.27 (SD=2.02) in the post-test and M=4.11 (SD=2.00) in the follow-up-test, which demonstrates a significant gain from the pre- to the post-test ($t_{(df=265)}$ = -9.88; p < .001; d=.77) and no significant difference between the post- and the follow-up-test. EG-students reached a mean of M=5.42 (SD=2.24) in the post-test and M=5.06 (SD=2.32) in the follow-up-test, again showing a significant gain from the pre- to the post-test ($t_{(df=254)}$ = -17.06; p < .001; d=1.37), and also a significant difference between the post- and the follow-up-test ($t_{(df=254)}$ = 2.85; p = .005; d=.16).

Table 3. Overview of the means and standard deviations of students' measures on knowledge. (n.s. not significant, * significant (p<.05), ** highly significant (p<.01), *** very highly significant (p<.001))

	Control Group		Experimental Group		
	M	SD	M	SD	
pre-test	2.93	1.38	2.90	1.33	n.s.
post-test	4.27	2.02	5.42	2.24	*** d=.54
follow-up-test	4.11	2.00	5.06	2.32	*** d=.44

These differences between the CG and the EG in the knowledge test revealed to be significant for the post-test ($t_{(df=519)}$ = -6.15; p < .001; d=.54), as well as for the follow-up-test ($t_{(df=519)}$ = -5.04; p < .001; d=.44). For an overview of students' measures on knowledge in both groups refer to Figure 2, as well as Table 3.
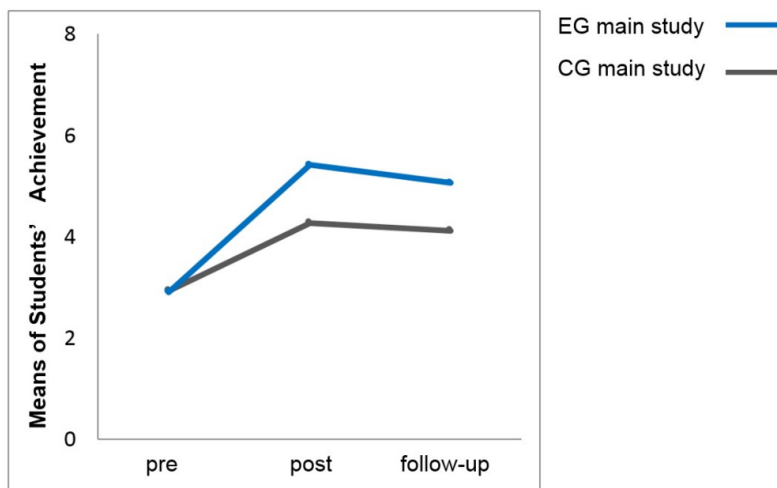
Figure 2. Means of students'measures on knowledge in the pre-, post- and follow-up-test subject by CG and EG.

Analysis of interest and self-concept in physics. The mean score for students' interest before the course was M=3.19 (SD=.86) on a scale from 1 to 5 within the entire sample, with M=3.08 (SD=.86) in the CG and M=3.29 (SD=.84) in the EG. This difference between the two groups is significant ($t_{(df=496)}$ = 2.72; p = .007, d=.25). After the course the mean score for students' interest in the CG was M=2.96 (SD=.82) in the post-test, representing a significant drop as compared to students' interest before the course ($t_{(df=243)}$ = 2.74; p = .007; d=.14). In the follow-up-test, students' interest was measured in the CG as M=2.89 (SD=.76). In the EG, the mean score for students' interest after the course was M=3.09 (SD=.85) in the post-test, also representing a significant drop as compared to students' interest before the course ($t_{(df=239)}$ = 4.55; p < .001, d=.24). In the follow-up-test students' interest was measured in the EG as M=3.00 (SD=.77).

However, even though interest values drop during the course in both groups, to be discussed later, the reported differences between the CG and the EG regarding interest were not significant, neither for the post-test nor for the follow-up-test. For an overview of students' measures on interest in both groups refer to Table 4.

Table 4. Overview of the means and standard deviations of students' measures on interest. (n.s. not significant, * significant (p<.05), ** highly significant (p<.01), *** very highly significant (p<.001))

	Control Group		Experimental Group		
	M	SD	M	SD	
pre-test	3.08	.86	3.29	.84	** d=.25
post-test	2.96	.82	3.09	.85	n.s.
follow-up-test	2.89	.76	3.00	.77	n.s.

The mean score for students' self-concept before the course was M=3.56 (SD=.89) within the entire sample, also on a scale from 1 to 5, with M= 3.50 (SD=.93) in CG and M=3.62 (SD=.84) in EG, which is not a significant difference. After the course the mean score for students' self-concept in the CG was M=3.35 (SD=.91) in the post-test. Again, this was a significant drop in self-concept as compared to before the course ($t_{(df=243)}$ = 3.30; p = .001, d=.16). In the follow-up-test, the average self-concept was measured as M=3.22 (SD=.97). The mean score for students' self-concept in the EG after the course in the post-test was M=3.55 (SD=.89), which was not a significant difference in self-concept as compared to before the course. In the follow-up-test the average self-concept was measured as M=3.38 (SD=.92).

Here, values for self-concept only drop significantly in the CG but not in the EG during the course. The reported differences between the CG and the EG regarding self-concept were significant for the post-test ($t_{(df=486)}$ = -1.99; p = .048; d=.22), but not for the follow-up-test. For an overview of students' measures on self-concept in both groups refer to Table 5.

Table 5. Overview of the means and standard deviations of students' measures on self-concept. (n.s. not significant, * significant (p<.05), ** highly significant (p<.01), *** very highly significant (p<.001))

	Control Group		Experimental Group		
	M	SD	M	SD	
pre-test	3.50	.93	3.62	.84	n.s.
post-test	3.35	.91	3.55	.89	* d=.22
follow-up-test	3.22	.97	3.38	.92	n.s.

In-Depth Data Analysis.
As stated above, the descriptive analysis of the pre-test revealed significant trend differences in the learning preconditions between the CG and the EG concerning interest and cognitive abilities. Consequently, for the in-depth statistical analysis we conducted a regression analysis to test a possible relation between these control variables and the dependent variable. If necessary, the control variables were taken into account as covariates.

Analysis of conceptual understanding of mechanics. With respect to the items of the knowledge test, the regression analysis showed pre-interest (post: β = .17; t(486) = 3.84; p < .001; follow-up: β = .15; t(486) = 3.31; p = .001) and cognitive abilities (post: β = .21; t(486) = 4.82; p < .001; follow-up: β = .20; t(486) = 4.60; p < .001) to be relevant predictors of the results after the course. Consequently, a repeated measures ANCOVA was conducted on two levels, with the dependent variable achievement on the knowledge test, the independent variables group, gender and teacher, as well as the covariates pre-interest and cognitive abilities. This revealed a significant effect with a small effect size of the covariates (pre-interest: F(1; 449) = 4.76; p = .030; part η^2 = .01, cognitive abilities: F(1; 449) = 15.73; p < .001; part η^2 = .03). Also the independent variables group (F(1; 449) = 30.86; p < .001; part η^2 = .06) and teacher (F(9; 449) = 6.21; p < .001; part η^2 = .11) had a highly significant influence with a medium effect size, while the independent variable gender (F(1; 449) = 10.91; p = .001; part η^2 = .02) had a highly significant influence with a small effect size. Moreover, a significant interaction effect between the variables group and gender was discovered (F(1; 449) = 4.00; p = .046; part η^2 = .01).

In order to more precisely examine at which level these significant differences could be found, a univariate ANOVA was conducted for each post-test and follow-up-test with the dependent variable achievement on the knowledge test (in the post-test and the follow-up-test respectively), the independent variables group and gender, the random factor teacher, as well as the covariates pre-interest and cognitive abilities.

For the post-test, the influence of the group was highly significant with a large effect size (F(1; 9,94) = 15.64; p = .003; part η^2 = .61). Another significant effect with a similarly large effect size was due to the influence of the teacher (F(9; 9,03) = 3.22; p = .048; part η^2 = .76). Although gender was a highly significant predictor of achievement in the post-test, the effect size was only very small (F(1; 465) = 8.42; p = .004; part η^2 = .02). An interaction effect of gender and group could not be found for the post-test achievements (F(1; 465) = .43; p = .52; part η^2 = :00).

For the follow-up-test, the influence of the group was significant with a large effect size (F(1; 9,78) = 5.37; p = .044; part η^2 = .35). The influence of the teacher as a significant effect was no longer found (F(9; 9,03) = 1.81; p = .196; part η^2 = .64). Gender, however, remained a highly significant predictor of achievement on the post-test with a small effect size (F(1; 465) = 7.18; p = .008; part η^2 = .02). Also, an

interaction effect of gender and group could now be found for the follow-up-test achievements (F(1; 465) = 3.98; p = .047; part η^2 = .01).

Additionally, the interaction effect of gender and group was examined in more detail. A comparison of the results regarding gender revealed the following: As far as the pre-test was concerned, girls were significantly outperformed by boys on the knowledge test in the CG (t$_{(df=264)}$ = 3.00; p = .003) as well as in the EG (t$_{(df=253)}$ = 3.60; p < .001). While this advantage remained apparent in the CG (post: t$_{(df=264)}$ = 2.77; p = .006 and follow-up: t$_{(df=264)}$ = 3.93; p < .001), no more significant differences could be found after the course in the EG (post: t$_{(df=253)}$ = 1.35; p = .178 and follow-up: t$_{(df=253)}$ = 166; p = .098).

Analysis of interest and self-concept in physics. A primary regression analysis showed that in contrast to cognitive abilities (post: β = .03; t(472) = .77; p = .439; follow-up: β = .04; t(473) = .92; p = .360), pre-interest (post: β = .62; t(472) = 17.06; p < .001; follow-up: β = .55; t(473) = 14.44; p < .001) had significant influence on the measure of interest in both the post- and the follow-up-tests. Therefore, a repeated measures ANCOVA was conducted on two levels, with the dependent variable interest, the independent variables group, gender and teacher, as well as the covariate pre-interest. Thus a highly significant influence of pre-interest was revealed (F(1; 433) = 278.74; p < .001; partη^2 = .39). When controlling for gender, however, the students' group assignment had no significant influence on their interest after the course (F(1; 433) = .92; p = .339; partη^2 = .00). To sum up that means that even though a decline in interest can be seen, no statistical difference between EG and CG can be detected for interest.

A secondary regression analysis showed that cognitive abilities (post: β = .10; t(458) = 2.57; p = .011; follow-up: β = .06; t(470) = 1.48; p = .139) and pre-interest (post: β = .54; t(458) = 13.79; p < .001; follow-up: β = .51; t(470) = 12.94; p < .001) had a significant influence on the measure of self-concept in the post- and the follow-up-tests. For this reason, both covariates were included in the repeated measures ANCOVA on two levels and the significant influence of both cognitive abilities (F(1; 407) = 4.98; p = .026; part η^2 = .01) and pre-interest (F(1; 407) = 163.62; p < .001; part η^2 = .29) was confirmed, whereas the independent variable group had no significant influence (F(1; 407) = .60; p = .440; part η^2 = .00). Again here, even though a decline in self-concept can be stated, statistical analysis shows no differences between EG and CG.

Discussion

As described above, for the development and implementation of the 2DD curriculum, results from research on students' preconceptions and on conceptual change have been combined. Criteria, to be met by a mechanics curriculum, have been derived from the analysis of the theoretical background and diSessa's concept of p-prims in particular. Thereafter ideas for a curriculum were identified from the literature; in particular, a dynamical and a two-dimensional approach seemed promising. Moreover, results from best practices in physics teaching have been integrated, such as hands-on experiments and a simulation.

Of course a lot of fine tuning of these ideas for a middle school classroom has been necessary. Only after several studies done in our research groups during the last decades, an alternative curriculum following the 2DD content structure could be achieved which we found was worth being assessed in the large-scale study reported in this paper. For this study we put the idea from Ausubel's quote "The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly." (Ausubel, 1968, page vi) into practice in our research question: Does a curriculum, which constructively uses students' conceptions as resources to build on, enhance middle school students' conceptual understanding of Newtonian mechanics, while interest and self-concept are not affected? We formulated the following hypothesis: "Teaching a curriculum which uses

students' conceptions as resources results in a better conceptual understanding of mechanics, while interest and self-concept are not affected."

Although the independent variable group was a significant predictor for students' conceptual understanding of mechanics, it was not for students' interest and self-concept in physics. When controlling for the relevant covariates, no significant influences of the group on students' interest and self-concept were detected after the course. We have to concede, that interest as well as self-concept declines during the study. This is a typical effect which can be seen in most science classrooms. And the evidence we presented shows, that also the use of the 2DD curriculum does not change this. So a better understanding does not automatically foster interest or self-concept. Even though the analysis showed no statistical differences between CG and EG in terms of interest or self-concept, the hypothesis cannot simply be accepted.

We found that by the use of the alternative curriculum following the 2DD content structure it is possible to teach Newtonian mechanics to 13-year-old children in a way, that they reach a promising level of conceptual understanding. We consider this in itself a major result of our project, because it has been shown repeatedly that even after instruction the learning outcomes are often fragmentary. Our data suggests that the alternative curriculum following the 2DD content structure is more effective than the traditional teaching sequence. Specifically, we found significant differences between the CG and the EG in terms of conceptual understanding (with effect sizes on the desired level), both taught by the same teachers over the same period of time. This stays true even when controlling for relevant covariates. Thus by using the alternative curriculum, physics teachers can help their students to reach a significantly higher conceptual understanding of mechanics, a notoriously difficult topic. In our opinion, a very promising result.

Furthermore, a gap between the performances of boys and girls on the subject before the course was revealed. While the achievement gap between boys and girls widened even further when taught according to the traditional curriculum, boys and girls learned equally well when taught according to the alternative 2DD curriculum. Even if items which are known to be gender-sensitive (Traxler et al., 2018) are excluded from our analysis, this effect prevails. We cannot easily give a reason, why the 2DD curriculum seems to close the gender gap. One possibility could be that girls react more sensitively with regards to approachability and comprehensibility of physics instruction. These results too, are promising.

In addition, our research project has also produced teaching materials which seem effective and are now freely available for physics teachers. All 10 teachers stated after the study that they would continue teaching according to the new curriculum. Some teachers also acted as multipliers in their schools. Consequently, our project has already led to the integration of the 2DD curriculum into the new syllabus of Bavaria[6].

Implications and Limitations

In summary, the results indicate that the guidelines we used for the construction of the 2DD curriculum were effective. The same we think is true for our orientation in diSessa's framework of conceptual change, which states that a mental structure has yet to be built using the fragmented p-prims of students' naïve ideas (diSessa, 1993). Our findings support this theory of a plurality of isolated ideas that are activated or not activated depending on the context. Our curriculum was designed intentionally to avoid the activation of inappropriate preconceptions while at the same time activating preconceptions that are appropriate, in the sense that they can be used in the development of a scientific understanding. We posit that this design feature helped to construct an effective curriculum that initiates a scientific mental structure even among young students in grade seven.

We concede, however, that we cannot say which aspects of the alternative curriculum are responsible for the effects achieved. This is in our opinion not due to a faulty design of the study, but it is an inherent problem in a quasi-experimental field study where complete control of all variables is naturally limited. There is reason to believe that the careful use of students' ideas and the omission of hindrance aspects (like the use of acceleration or premature examples with falling motion) as well as other aspects (such as the dynamical approach, the two-dimensional approach, the alternative version of Newton's second law, or the representation of velocities and forces with arrows) sum up to get the reported results. While these results are (in comparison to other quasi-experimental field studies) quite large, each single aspect might only have minor effects. On the one hand, with this point in mind, a critic of our work could regard the study as inadequate. On the other hand, it could also be regarded as a preliminary study that furthers research. Since we have shown that it is possible to improve instruction on Newtonian mechanics, subsequent studies with an adjusted design can turn to probing the effects of individual aspects. This holds also true for future studies regarding interest and self-concept. The research presented showed evidence, that the 2DD curriculum and traditional curricula have comparable effects on interest and self-concept. But that means, that interest and self-concept decline significantly in parts during both courses over approximately ten weeks, which is a major concern. So for future redesigns of the 2DD curriculum, this has to be taken into account. One possible solution could be, to focus even more on relevant contexts and add more interesting problems, for example with interesting videos. But at least it is reassuring, that the use of the 2DD curriculum does not makes the drop in interest and self-concept worse.

As for generalisability, the teachers' education has to be taken into account. Because in Bavaria all middle school physics teachers have studied this subject as one of two majors during five years at university, it is not clear if other teachers can adapt to the alternative curriculum equally well. Moreover, as the teachers' participation in the project was voluntary, potential selection bias must be considered. It is possible that the teachers participated because they already felt a strong need for revised materials and hence were less enthusiastic to use the traditional teaching sequence in the CG than the 2DD content structure in the EG. Although this might have had an influence on the learning outcome, it might also be the case that this influence is counterbalanced by the teachers' experience with the material in the CG and their lack of experience with the material in the EG. This being particularly noteworthy for those who had already been teaching the traditional sequence for many years.

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Footnotes

[1] In Germany the distinction between speed and velocity is especially difficult, as both words translate into the same expression "Geschwindigkeit". In this regard, a discussion about the influence of language on learning science is particular noteworthy. As it would go beyond the focus of this paper to unfold this perspective here, please refer for example to Itza-Ortiz, Rebello, Zollman & Rodriguez-Achach (2002) or to Suzuki (2005).

[2] The approach is one of several possibilities for the introduction of mechanics (see Eisenbud, 1958; Westphal, 1967). Westphal refers to ideas by Ernst Mach (s. also Weinstock, 1961) and is also similarly used in the PSSC Curriculum (Physical Science Study Committee, 1960).

[3] We decided not to use the word „vector" in the curriculum, since the topic of vector algebra is only introduced in the mathematics classrooms several years later. But preliminary studies showed us that,

even for 13-year-olds, it is no problem to use arrows to describe the direction and the magnitude of a velocity.

[4] In grade 7 the goal is for the students to associate force with the movement change rather than with the movement itself, so that Newton's Second Law is central. In higher education physics, Newton's Second Law is usually considered a definition of force. Then, the only purpose of the First Law is to find an inertial system in which the Second Law holds. The First Law is thus a paraphrase of the definition of inertial systems, (which are not taught in grade 7).

[5] Items 2, 4, 5, 6, 7, 13 und 20 of the first version on the FCI (Hestenes, 1992)

[6] http://www.lehrplanplus.bayern.de/fachlehrplan/gymnasium/8/physik