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Chapter 27

Gender Differences in Science Education: The Double-Edged Role of Prior Knowledge in Physics

Markus Dresel, Albert Ziegler, Patrick Broome and Kurt A. Heller

Abstract

This study investigated gender-related differences in prior knowledge in physics that were present before the start of initial physics instruction and the influence of prior knowledge in physics on future achievement in 8th grade German physics courses. The present data were collected prior to initial physics instruction. Mildly gifted students (average IQ = 111) in the 7th grade of German Gymnasium (547 girls and 641 boys) were asked about their prior knowledge in physics. In comparison to boys, many girls achieved lower overall-scores in the applied test of prior knowledge in physics. These findings were strongest for questions dealing with the more theoretical concept of mechanics. Only moderate gender-differences appeared in areas concerning everyday experiences. As expected, girls received poorer mid-year grades. In predicting subsequent achievement in physics, neither prior knowledge nor ability explained the gender differences evident in this study. Furthermore, the results verify that gifted children, who have acquired substantial amounts of prior knowledge in physics, have problems replacing (faulty) naive physical concepts with proper concepts. This difficulty was more pronounced among the boys.

Introduction

Gender-related differences are well documented in achievement in physics (see Ziegler & Heller, 1997). Traditionally, girls produce poorer scholastic performances and receive lower marks than boys and these performance differences intensify over the course of the scholastic process. The consequences become obvious when viewing participation rates in advanced courses offered by German Gymnasiums (secondary level college preparatory schools). The percent of girls participating in physics courses in Germany for the school year 1995-96 was only 14.3%.[1] Similarly, low participation rates turn up for comparable university majors and career fields.

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[1] Source: Information related per telephone by the Bavarian Bureau for Statistics and Data Processing.

These differences in female and male participation rates in the science area can hardly be explained by ability differences (cf. Heller & Ziegler, 1996). For example, even high ability girls perform less well than their male counterparts (e.g. Benbow & Lubinski, 1995; Ziegler, Heller & Broome, 1996). Thus, explanations for different achievement results in physics based on the giftedness variable obviously cannot work. However, studies show that the hypothesis of different cognitive abilities of boys and girls required for such a subject as physics is not adequately supported, but rather provides evidence for comparable abilities (Srocke, 1989; Callahan, 1991; Beerman, Heller & Menacher, 1992).

Although the causes for gender differences in physics are still disputed in the literature, the focus of research has shifted during the last few years towards explanations based on differing self-related cognitions and more socialization oriented approaches. Noteworthy among the latest explanatory theories (for an overview see Ziegler & Heller, 1997; Beerman et al., 1992) is the amount of importance attached to various differing socialization experiences attributed to gender which can, to a certain extent, be effective even before physics instruction has started.

These socialization experiences can be subdivided into two components: *self related cognitions*, particularly attribution style, self-concept or implicit theories of abilities; and *previous experiences in physics* such as in optics or electronics. Research shows that boys prove themselves to be significantly more adept at both of these components (Ziegler, Heller & Broome, 1996; Dweck, 1986; Dweck & Licht, 1980; Fennema & Sherman, 1977; Eccles, Wigfield, Harold & Blumenfeld, 1993; Wigfield & Eccles, 1994).

In this study we consider previous experience as well as prior knowledge in physics, and investigate whether gender-specific differences in these variables can explain the performance differences observed between boys and girls in physics. We are also interested in performance development of gifted children who have substantial amounts of prior knowledge in physics resulting in a large amount of involuntarily naive, faulty physical knowledge. Does prior knowledge turn out to be obstructive or conducive in these cases? In cases where prior knowledge acts obstructively, can these students compensate for it with their talents? Simultaneously, the purpose of the work is to provide a contribution to the ongoing discussion of didactic in physics (e.g., Greeno, 1997; Wiesner, 1995) as to whether one can, by compensating for prior knowledge differences, expect to see a reasonable improvement in the present situation of girls with respect to physics.

Prior Knowledge in Physics

It is certainly true that boys have a larger amount of previous experience with physics, as well as a naive understanding of more physical concepts than girls. This is not necessarily an advantage as proven by research findings into naive physical concepts (Carey, 1985a/b; DiSessa, 1983; Gentner & Gentner, 1983; Larkin, 1983; McCloskey, 1983; Vasniadou & Brewer, 1987; West & Pines, 1985; Ziegler & Ziegler, 1991). Although these intuitive representations contain information on how the entities of a specific area of physics interact with one another as well as on how these interactions can be explained, they are frequently incomplete and false. Completely different and, to an extent, contradictory naive models of the same phenomenon which are activated in different contexts can coexist (Williams, Hollan, & Stevens, 1983).

It has been shown that naive physical models are difficult to displace, even through structured learning (Alvermann & Hague, 1989; Clement, 1983; DiSessa, 1983). In some studies one sees decisive evidence that the error rate decreases as a result of physics instruction (McCloskey, 1983; Ziegler & Ziegler, 1991) although the types of errors made remain unaffected. In other studies the physics instruction had absolutely no bearing on the desired performance (Kister Kaiser, Proffitt & Anderson, 1985). Set against the background of these findings, the theory that the advantages demonstrated by boys with respect to physics are due to their larger wealth of experience must be viewed skeptically since prior knowledge can also act as an impediment. A data-collection in the naturalistic field of physics education at the 8th grade level of German Gymnasiums was chosen to explore the following research questions: Does the amount of prior knowledge in physics, present before the start of the initial physics instruction differ between boys and girls and does it reveal a gender-related differing impact on future achievement?

Method

Measures

Diagnosis of giftedness in physics. To establish the level of cognitive talent, the intellectual abilities of the subjects were assessed with a German version of the quantitative subscales of the Cognitive Abilities Test (CogAT) for 4th to 13th graders (Kognitiver Fähigkeitstest für 4. bis 13. Klassen, Berufsschüler und Studenten, KFT 4-13+) developed by Heller, Gaedike and Weinläder (1985, 2nd ed.). We selected the CogAT because it is characterized by excellent psychometric properties and the quantitative abilities which can be measured with the CogAT are nearest to those abilities required in (German) physics courses.

Achievement. To determine the influence of prior knowledge on actual scholastic achievement we considered the marks the students received in physics for the grading period encompassing the first half of the 8th grade. In addition, the marks the students received for participation in physics class were also at our disposal.

Test of prior knowledge in physics. For assessing the prior knowledge in physics we translated parts of the TIMSS (Third International Mathematics and Science Study). The questions of the TIMSS-Natural Science tests determine, even though they are easy to solve, the ability to understand physical phenomena. Neither the application of formulas nor mathematical computation is required. The questions (see Table 1) include exercises which:

- concern everyday experiences that relate to physics, knowledge from areas familiar to the students (Questions 1-5).

Table 1: Contents of the test of prior knowledge in physics.

Item	Question	Specific field of physical knowledge (theme)
Direct everyday experience		
(1)	Four illustrations depict two children of different weights sitting in different spatial intervals with respect to the fulcrum of a crossarm. One is to decide which of the illustrations represents a condition of equilibrium.	Lever principle
(2)	The illustration depicts two pots of boiling water. One of the pots receives additional heat energy. One is to determine if this additional heat energy shortens the cooking time of the contents of the pot.	Constancy of the boiling temperature
(3)	Four water filled containers with variously sized water surface are depicted. One is to indicate the container which allows for the quickest rate of evaporation.	Dependence of quiescent evaporation quantity on surface area
(4)	Three possible ways to position two batteries in a flashlight are presented. One is to indicate which ordering forms a closed circuit and results in the successful illumination of the flashlight.	Polarity of batteries: Positive and negative poles of a battery as properties of an electrical circuit
(5)	The purpose of the second hole in a can of condensed milk is to be explained.	Concept of Pressure
Comprehension of a physical phenomenon with the aid of a diagram or illustration		
(6)	Five thermometers with different temperature scales are represented. One has to decide which thermometer can best indicate the exact measurement of body temperature.	Body temperature, exactness of measurements; comprehension of a physical phenomenon with the aid of an illustration
(7)	The displacement-time-diagram of an ant moving with constant velocity is represented. The ant moves forward until time passed is $t = 20$ sec., the distance covered when $t = 30$ sec. is to read off.	Movement with constant velocity; displacement-time-diagram
Concept of the Mass/Mechanics		
(8)	The direction of movement followed by a stone released from a specified height on the moon is to be indicated.	Gravitation on the moon
(9)	One kg of sugar is dissolved in 10 kg of lemonade. One is to determine the weight of this solution.	Independence of mass from solution state.
(10)	A ball is shown rolling out of a spiral formed channel. One is to determine the direction of the ball after it leaves the channel.	Mass moment of inertia
(11)	One is to determine the weight of a glass of water after ice-cubes which have been floating in the water have melted.	Independence of mass from the state of aggregation

- measure the ability to understand physical circumstances with the assistance of diagrams and illustration (Questions 6-7).
- represent specific subdivisions of physics requiring a conceptual understanding. These were taken from the area of mechanics, particularly concerning how mechanics relates to the concept of mass (Questions 8-11).

Subjects

The results stem from an investigation conducted with 547 female and 641 male students in Bavarian high schools (Gymnasium) at the end of the 7th grade, i.e., shortly before physics instruction begins. All the testing was conducted in paper and pencil test format, completed in the classroom during regular lessons. The average KFT-value was $M = 111$ ($s = 11.3$).

Results

The results presented in Figure 1 show that both male and female students have considerably less prior knowledge regarding exercises which deal with mechanics and the concept of mass (on the average 49% correct solutions) than for exercises which relate to phenomena involving areas of direct experience (78% correct solutions). Exercises which demand the comprehension of physical phenomena represented by diagrams and illustrations (72% correct solutions) also indicate a large degree of available prior knowledge. The differences between prior knowledge regarding mechanics and the concept of mass and prior knowledge regarding direct experience are more prominent among the girls than among the boys.

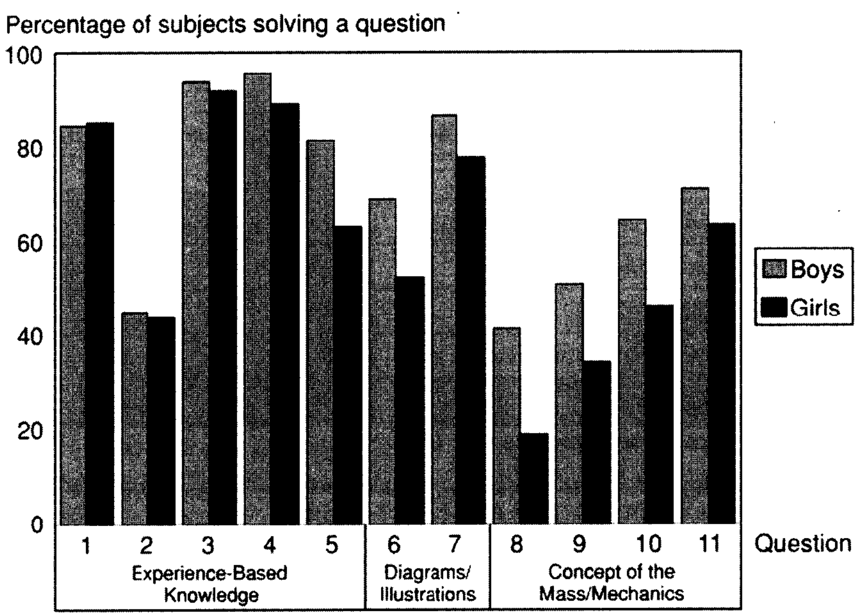

Figure 1: Results of the test of prior knowledge in physics.

Gender Differences With Respect to Knowledge of Physics Before the Start of the First Physics Course

Furthermore, Table 2 indicates that the girls in general had a considerably smaller amount of physics related prior knowledge at their disposal than the boys. With the exception of questions 1 (lever principle), 2 (constancy of boiling temperature) and 3 (evaporation), significant statistical differences ($p < .01$, exception: Independence of mass from the state of aggregation was significant only on a 5%-level), could be proven to support gender differences. While 60% of the boys solved at least 8 of the 11 exercises correctly, the corresponding solution rate for the girls was only 34%. The most pronounced gender differences appeared in exercises dealing with mechanics and the concept of mass. These concepts were covered by questions 8 (gravitation on the moon), 9 (independence of mass from solution state) and 10 (mass moment of inertia) where differences of up to 23 percentage points were recorded. Large differences in solution rates were also uncovered by questions 5 (concept of pressure) and 6 (body temperature).

Table 2: Results of the test of prior knowledge in physics: Percentage of subjects solving the respective items.

Item	Theme	Boys	Girls	χ^2	p
Direct everyday experience					
(1)	Lever principle	84	85	0.1	.80
(2)	Constancy of the boiling temperature	46	45	0.1	.82
(3)	Evaporation	94	93	0.8	.37
(4)	Electrical circuit in a flashlight	96	89	15.5	.00**
(5)	Concept of Pressure	81	63	40.4	.00**
Comprehension of a physical phenomenon with the aid of a diagram or illustration					
(6)	Body temperature	69	53	28.5	.00**
(7)	Movement with a constant velocity	86	78	12.1	.00**
Concept of the Mass/Mechanics					
(8)	Gravitation on the moon	42	19	58.6	.00**
(9)	Independence of mass from solution state	51	34	26.8	.00**
(10)	Mass moment of inertia	64	46	33.5	.00**
(11)	Independence of mass from the state of aggregation	71	63	5.9	.02*

Note: * $p < .05$. ** $p < .001$. $N = 1188$ (641 boys, 547 girls).

On the other hand, exercises which touched on phenomena dealing with areas of direct everyday experience did not, with the one exception of question 5 (concept of pressure), allow for the establishment of gender differences. No statistically significant differences between boys and girls could be made for questions 1 (lever principle), 2 (constancy of boiling temperature) or 3 (evaporation). A slight discrepancy of 7 percentage points was recorded for question 4 (electrical circuit of a flashlight).

Exercises which demanded the comprehension of physical phenomena represented through diagrams and illustrations revealed statistically significant gender differences. These differences were not as distinct as the differences recorded for exercises involving mechanics and the concept of mass. Question 7 (movement with a constant velocity), which deals with a typical physical illustration (the displacement-time-diagram), resulted in a rather small gender difference of 8 percentage points. In contrast, the difference in solutions for question 6 (body temperature), which demanded understanding the concept of exact representation, reached a full 16 percentage points.

Gender Differences in Scholastic Performance

Mid-year grading reports in the subject of physics do confirm the expected gender differences. As shown in Figure 2, the boys received average grades of 2.7 while the girls received an average score of 3.0 (based on a scale of 1.0 to 6.0 with 1.0 being the highest grade possible). The difference could be statistically proven to the 1% level. On the other hand, participation rates in physics courses demonstrated a negligible (not statistically significant) lead for the boys. Both genders could reach a mark here of about 2.5 (see Table 3).

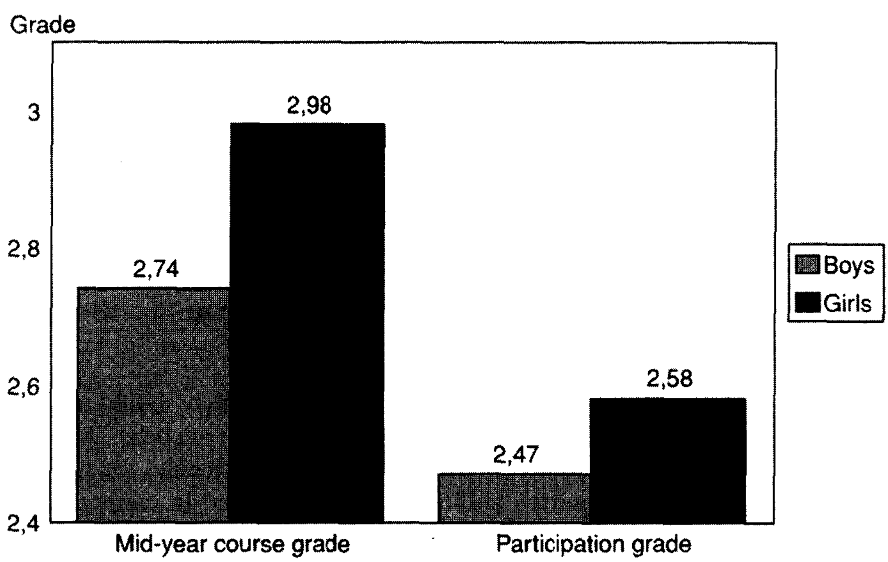

Figure 2: Gender differences in mid-year course grades and participation grades for 8th grade in physics.

In the next phase of the analysis the quality of prior knowledge in physics and talent level in predicting marks in physics will be examined with the help of a regression analysis.

Table 3: Mid-year course grades and participation grades for 8th grade in physics.

Grades for group I (Boys) and group II (Girls)				
Grade	**Boys**	**Girls**	***t (df)***	***p***
Mid-year course grade	2.7	3.0	-3.6 ($df = 813$)	.00**
Participation Grade	2.5	2.6	-1.5 ($df = 817$)	.18

Note: ** $p < .001$. The Grades are based on a scale of 1.0 to 6.0 with 1.0 being the highest grade possible.

The percentage of correctly answered exercises on the test of prior knowledge in physics did not turn out to be a suitable predictor for either the boys or the girls. Therefore the average values for each of the three exercise groups in the test of prior knowledge in physics was determined for each participant and entered into the regression equation to test their capacity for predicting mid-year grades. Although these three averages did not improve the predictive power of the test of prior knowledge in physics for the grades achieved by the boys, the performance on exercises dealing with "Physical phenomena in diagrams/illustrations" was confirmed as being suitable to predict the physics grades of girls ($R = .29$, *beta* = -.27, $p < .05$). On the other hand, the other two exercise areas did not reveal the predictive quality for the girls (see Table 4).

Table 4: Results of the regression analysis omitting cognitive ability predictors.

	Mid-year grades in physics					
	Total		**Boys**		**Girls**	
Multiple R	.27		.25		.29	
Predictors	*r*	*beta*	*r*	*beta*	*r*	*beta*
Experience-based knowledge	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Concept of the Mass/Mechanics	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Diagrams/Illustrations	-.25	-.23	n. s.	n. s.	-.28	-.27

Note: n.s. not significant; $p < .05$.

After the inclusion of individual cognitive abilities (which should actually be good predictors of scholastic achievement) in the regression analysis, it was unexpectedly shown that these had no significant predictive influence for the physics grades among the boys. Cognitive abilities when considered in conjunction with the exercise areas of the test of prior knowledge in physics obtained for the girls could explain 25% of the variance for the physics grades achieved by the girls (see Table 5).

Discussion and Didactic Implications

The results of our study prove that many students, both boys and girls, have a certain amount of prior knowledge at their disposal before their initial exposure to physics courses. As expected, significantly less previous knowledge can be confirmed for areas of physics which draw on direct experiences as well as those which require conceptual comprehension for both genders. Two aspects of our resulting data sets seem to be especially significant. Therefore, the following discussion concentrates on *gender differences* and the *ambivalent nature of prior knowledge*.

Table 5: Results of the regression analysis including cognitive ability predictors.

	Mid-year grades in physics					
	Total		Boys		Girls	
Multiple R	.35		.27		.50	
Predictors	*r*	*beta*	*r*	*beta*	*r*	*beta*
Experience-based knowledge	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Concept of the Mass/Mechanics	n. s.	n. s.	n. s.	n. s.	n. s.	n. s.
Diagrams/Illustrations	-.25	-.18	n. s.	n. s.	-.28	-.23
Cognitive Abilities	-.28	-.25	n. s.	n. s.	-.44	-.42

Note: n.s. not significant; $p < .05$.

A familiar image of gender differences in the area of physics is reconstructed with the results of our study. This is especially evident in areas where experience plays a lesser role. Mainly in conjunction with themes which are more complex and touch on subjects which are further removed from everyday occurrences, the employment of instructional forms which depend on previously obtained scholastic knowledge poses the distinct danger of discriminating against girls. A form of instruction which focuses on prior knowledge seems to be preferred for subjects which encompass phenomena which can be experienced in one's environment since gender differences are weakest here. Such thematic areas offer the opportunity to avoid putting the girls at a disadvantage (Ziegler, Broome, Dresel & Heller, 1996).

The duplicitous nature of the importance of prior knowledge in physics for later achievement in physics courses is confirmed by the regression analysis. In the introductory section it was mentioned that most naive concepts concerning physics are faulty and can only with difficulty be corrected through physics instruction. According to Baumert, Lehman et al. (1997) not every competence which is central to the understanding of the basic principles of modern mathematics and natural sciences can be casually acquired in the normal daily activities of adolescents. Their acquisition require guided long-term, systematic learning processes. Therefore, it is not striking to see that prior knowledge in physics has only a limited capacity to predict physics course grades. Since it is presumed that students gifted in the subject have occupied themselves more intensely with questions of a physical nature before they have been introduced to formal physics instruction, they possibly have more naive physical concepts at their disposal than average students. Despite (or perhaps better: due to) their greater talent they are more intensely confronted with the problem of replacing naive knowledge with adequate physics concepts. It is obvious that with the inclusion of predictors of giftedness into the regression equation, no better predictor qualities could be obtained among the boys. The assessment of the double-edged role of prior knowledge is supported by the finding that the smallest gender differences appeared on exercises which were drawn from the areas of direct experience. This possibly unexpected finding, however, confirms that a larger – more mistake prone – wealth of experience (Ziegler et al., 1996) does not necessarily lead to adequate physics-based knowledge.

In summation, it is obvious that boys have more prior knowledge in physics at their disposal than girls, but this does not explain the better grades they receive in physics courses. On the contrary, our data indicates that this prior knowledge, due to its incomplete and faulty nature, acts to impede the acquisition of adequate physical concepts for students already rich in experience, which is especially true for gifted students. The didactic answer for the dismantling of gender differences in physics can, therefore, not be found in the unreflected taking up of physical experiences and particularly not those experiences in areas which appeal particularly to females. There is also a great danger here of initiating learning processes on the basis of the students' prior knowledge, which is potentially based on deficient naive concepts. In order, however, to prevent misunderstandings, we do not want to advocate the exclusive discussion of topics in physics which are remote from common experience. The anchoring of subject matter in the common knowledge of the students is a didactic goal which we find to be very meaningful, and for which the effectiveness in arousing and maintaining students interest in physics is indisputable. Baumert (1996) claims that the best predictor for technical problem solving has proven to be scholastic knowledge dealing with natural phenomena. Schools and teachers are challenged to intensify their educational activities to open the imaginations of growing children to questions based in the natural sciences. One should, however, always insure that the learning process is initiated with and based on *adequate* physical concepts which are presented by the teacher.

The results of our study also show that one can come close to shutting the gender gap in physics by compensating for the deficits in prior knowledge among the girls, seems to be illusionary. As depicted in the regression analysis, neither prior knowledge nor talent level can explain the gender differences evident in physics course grades. These findings strongly support the assumption, that gender differences in physics achievement are more influenced by the second component of physics-related socialization experience: self related cognitions, such as domain-specific self-concept or attribution style connected with achievement results in physics. Based on this conclusion, we think that intervention treatments which bring about a change in the self-related cognitions of the girls offer more promise. Particularly, an improvement of dysfunctional attribution styles in physics (attribution retraining; for overviews see Försterling, 1985; Ziegler & Schober, 1997) seems to offer numerous promising and appropriate possibilities (Craven, Marsh & Debus, 1991; Heller & Ziegler, 1996).

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