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# Understanding Energy - An exploration of the relationship between measures of students' understanding of energy, general cognitive abilities and schooling

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## Abstract

Past research has examined students' understanding of energy at different stages of schooling. This research has led to the widespread view that students progress in their understanding of energy through a sequence of key ideas about energy. However, so far, it is unclear, whether this progression in understanding energy is a result of schooling or whether it is a result of maturation - in particular, as the role of general domain-unspecific cognitive abilities that improve with age, such as reading ability in the assessment of students' understanding of energy. In a re-analysis of data from N=1856 students of grades 6, 8 and 10 in German middle schools, we investigated, in addition to the amount of schooling, the impact of general cognitive abilities on measures of middle school students' understanding of energy. To do so we utilized a latent variable modelling approach. Our findings suggest that whereas students' understanding of energy is related to general cognitive abilities, this understanding is also considerably dependent on the amount of schooling. This finding corroborates findings from earlier studies that students' progression in their understanding of energy is indeed a function of schooling and not just a product of maturation.

**Keywords**
Energy understanding, cognitive abilities, Rasch Background Model

## Introduction

Energy plays a central role in science, as well as in our everyday lives (Chen, Eisenkraft, Fortus, Krajcik, Neumann, Nordine & Scheff, 2014). Energy is a core concept in many science disciplines and a concept cutting across all disciplines of science (National Research Council, 2012). Some of the most pressing societal issues are related to energy, such as the question of energy demand and supply as well as global warming (Chen et al., 2014; Driver & Millar, 1986). In order to understand these issues and make informed decisions, students need to develop a deep understanding of energy. Science educators and science education researchers agree that such understanding entails an understanding of four key ideas about energy: energy forms and sources, energy transfer and transformation, energy degradation, and energy conservation (Duit & Neumann, 2014; Duit, 1986; for an overview see Chen et al., 2014).

Science education researchers also agree that students' progress from an initial understanding of energy forms and sources to an understanding of energy conservation along the above sequences of ideas (e.g. Lee & Liu, 2010; Liu & McKeough, 2005; Neumann, Viering, Boone, & Fischer, 2013). There is disagreement, however, about the role of general domain-unspecific cognitive abilities on this development. Whereas Liu and McKeough (2005) suggest that students' progression depends to a significant extent on the development of general cognitive abilities (i.e. maturation), Neumann et al. (2013) interpret the observed progression solely as a product of schooling aimed at enhancing students' understanding of energy. In order to shed more light onto the question of schooling vs. maturation, we undertook in this study a re-analysis of the data collected by Neumann et al. (2013), investigating the influence of multiple variables (i.e. general cognitive abilities and amount of schooling) on the measures of students' understanding of energy.

### *Students' progression in developing an understanding of energy*

Much research has explored how students' progress in developing an understanding of energy throughout school (e.g. Dawson-Tunik, 2006; Lee & Liu, 2010; Liu & McKeough, 2005; Neumann et al., 2013; Nordine, Krajcik, & Fortus, 2011; for an overview see Chen et al., 2014). The first to provide insight into on how students' progress in developing an understanding of energy across multiple grades were Liu and McKeough (2005). After conducting a review of the literature on students' conceptions of energy at different age and grade levels, the authors re-analyzed data form the Third International Mathematics and Science Study (TIMMS; Beaton, Martin, Mullis, Gonzales, Smith & Kelly, 1996). The findings suggested that students' progress in understanding energy from non-normative ideas developed from everyday experiences such as the idea of energy as an activity by successively developing understanding of the following key (scientific) ideas: 1) energy forms and sources, 2) energy transfer and transformations, 3) energy degradation, and 4) energy conservation. These findings were corroborated by several other researchers in different contexts utilizing different strategies to assess students' energy understanding (e.g. Dawson-Tunik, 2006; Lee & Liu, 2010; Neumann et al., 2013; Nordine et al., 2011).

Despite leading to similar findings across different contexts and assessment strategies, previous studies differed in their assumptions about the relative roles of general domain-unspecific cognitive abilities and their development (maturation) in relation to the teaching about energy (schooling). Some researchers assumed the observed progression to be solely an artifact of instruction (e.g. Lee & Liu, 2010; Neumann et al., 2013; Nordine et al., 2011), whereas other researchers hypothesized that the progression was, at least in part, dependent on the development of students' general cognitive abilities (Dawson-Tunik, 2006; Liu & McKeough, 2005). Liu and McKeough (2005) for example assumed that understanding the individual ideas about energy required a certain stage in the development of students' general cognitive abilities and took their observation of somewhat distinct difficulties of items assessing different key ideas as evidence for their assumption. Neumann et al. (2013) utilizing a similar methodological approach as Liu and McKeough (2005), however, reported a particular overlap in item difficulty for items assessing different key ideas. This overlap has been interpreted as evidence for the (continuous) growth of an increasingly complex knowledge base resulting from instruction on energy (Neumann et al., 2013).

To date the question to which extent the observed progression is influenced by maturation and to which extent it is an outcome of schooling is still open; in particular, as none of the published research has considered the role of general cognitive abilities in assessing students' understanding of energy.

### *The role of general cognitive abilities in assessing students' understanding of energy*

In addition to domain-specific abilities (e.g. knowledge about energy) general domain-unspecific abilities play a particular role in solving domain-specific problems (e.g. Baumert, Lüdtke, Trautwein & Bruner, 2009; Helmke & Weinert, 1997; Weinert & Helmke, 1995). These general cognitive abilities include for example abilities related to language, reasoning, perception, or creativity (e.g. Carroll, 1993). Several attempts have been undertaken to organize these abilities into a hierarchical model of general cognitive ability with a single factor (g) representing the overall general cognitive ability of an individual (e.g. Carroll, 1993; Cattell, 1963; Jäger, 1973). This general cognitive ability can be represented by two somewhat distinct classes of abilities relating to 1) an individual's inherent cognitive capability such as the ability to think in a formal-logic (abstract) way (also known as crystallized intelligence, gc), 2) the products of general learning processes such as linguistical or mathematical abilities (also known as fluid intelligence, gf). Both classes can be further differentiated into individual abilities (Cattell, 1963; Cattell & Horn, 1978, see also Carroll, 1993). This is often done for crystallized intelligence which is differentiated into linguistical and mathematical abilities as these are – together with formal-logic thinking abilities – considered to be most predictive for school achievement (e.g. Heller & Perleth, 2000; Thorndike, 1997). Regarding the development of these three abilities, research shows that these abilities usually develop pretty quickly during childhood, with development flattening during adolescence (e.g. Baltes, 1984; Schneider, 2004; Schneider, 2002).

As a consequence it may very well be that students' achievements on energy assessments and thus the progressions reported by Liu and McKeough (2005) or by Neumann et al. (2013) are due to the higher levels of abstract thinking required by the more elaborate key ideas about energy (which only students in higher grades have reached). Another possibility is that as the key ideas of energy conservation and energy dissipation require a higher level of quantitative reasoning, students' quantitative abilities may affect their performance. Finally, it could be that tasks assessing elaborate ideas such as energy conservation typically involve complex texts, requiring higher linguistic abilities. That is, the observed progression could be a by-product of maturation.

In order to obtain evidence about the extent to which the observed progression of students understanding of energy depends on maturation rather than schooling, we explored the effects of selected general domain-unspecific cognitive abilities on students' energy understanding over a range of grades. In doing so we provide information on an issue that has not been addressed in previous studies on students' progression in understanding energy.

## Methods

The study is a re-analysis of the data collected in a large-scale study on students' understanding of the energy concept (Neumann et al., 2013). In this re-analysis, besides looking at data on students' understanding of energy, we included also data on students' general domain-unspecific abilities that were not addressed in previous publications.

*Participants*

The data stem from N = 1856 students attending grades 6, 8 and 10 in Gymnasium middle schools in North Rhine-Westphalia, Germany. Gymnasium represents the most academic of three different school tracks in Germany. With graduation from Gymnasium, students acquire the eligibility to attend university. About one third of all students in one year go to Gymnasium schools (for a more detailed description of the German school system see Neumann, Fischer, Labudde & Viiri, 2014). Participants were sampled as whole classes of schools (and teachers) volunteering to participate. To control for school-specific effects on students' progression in understanding energy in each school, classes from grades 6, 8 and 10 were sampled. As a result, the data set included students from 70 classes from grades 6, 8 and 10 at eight different Gymnasium middle schools. Details on the distribution of students across schools and classes are available (as Table 4) in the online supplemental material to Neumann et al. (2013).

*Curriculum*

Science education in Germany is based on state-wide curricula. These curricula, however, resemble standards (e.g. National Research Council, 1996) more than actual instructional materials (Krajcik, Reiser, Fortus & Sutherland, 2015). The state-wide curriculum for North-Rhine-Westphalia places a particular emphasis on energy as a core concept of science. The curriculum defines what students should know about or be able to do with the energy concept respectively for the ends of grades 6, 8 and 10. According to this curriculum, by the end of grade 6 students should understand that objects in motion or at a certain height have energy and that energy manifests itself in other forms. Students should be able to describe energy transfer and transformation processes using energy transfer diagrams. Finally, students are supposed to understand how in every process some energy is converted into heat that spreads out across the environment. Energy conservation is not explicitly listed, but included implicitly as a prerequisite to students' understanding the idea of energy degradation (cf. Nordine, Fortus & Krajcik, 2011). The focus clearly lies on mechanics and thermodynamics. By the end of grade 8 students are expected to have developed a deeper understanding which in particular integrates an understanding of energy in the context of electricity (and partly in optics). By the end of grade 10 students are supposed to have developed an even deeper understanding of the four big ideas about energy. Specifically, students should be able to quantify the energy manifested in specific forms and to quantify energy transfer and transformation processes. Based on a quantitative understanding of the principle of energy conservation, students should be able to quantify energy degradation processes (e.g. by considering the efficiency of devices). Contexts include mechanics, electricity, thermodynamics and others such as nuclear physics.

### *Instruments*

Three different instruments were utilized to collect data from students in the study by Neumann et al. (2013): (A) the Energy Concept Assessment described in Neumann et al. (2013), (B) an instrument to assess students' linguistic abilities and (C) an instrument to assess students' formal-logic thinking and arithmetic abilities. Students' linguistic abilities were assessed with the reading ability test developed by Schneider, Schlagmüller and Ennemoser (2007), since in the context of multiple-choice assessments such as the Energy Concept Assessment, linguistic abilities mostly relate to reading abilities (e.g. Drechsel & Schiefele, 2005, see also Leutner, Klieme, Meyer, & Wirth, 2004). Subscales of the Kognitive-Fähigkeiten-Test (Cognitive Ability Test) by Heller and Perleth (2000) was used to assess students' formal-logic and arithmetic abilities.

#### Energy Concept Assessment

The Energy Concept Assessment was designed utilizing a bank of 120 items assessing students' understanding of the four key ideas about energy (see Figure 1 for a sample item and the technical handbook published as online supplemental material by Neumann et al., 2013, for the complete item bank). These items are grouped into 12 test booklets with 20 items each. Each student was administered one of these booklets. In order to be able to compare the achievement of students who were administered different booklets, two adjacent booklets (i.e. 1 and 2, 2 and 3,…, 12 and 1) shared a block of 10 identical items (for further details see Neumann et al., 2013).

*An airplane is flying through the air.*

*What could you state about the airplane from a physics point of view?*

○ *One can assign kinetic energy to the airplane because the airplane flies at a certain altitude.*

○ *One can assign kinetic energy to the airplane because the airplane has a certain speed.*

○ *One cannot assign any energy to the airplane because only living things possess energy.*

○ *One can assign kinetic energy to the airplane because the airplane gets lifted by the air.*

Figure 1. Sample Energy Concept Assessment item

#### Reading Ability Test

The Reading Ability Test was developed and validated by Schneider, Schlagmüller and Ennemoser (2007) for assessing and comparing the reading abilities of students from grade 6 to 12. The test provides information on students' reading speed (RS) and reading comprehension (RC). The test consists of a cloze text (i.e. a text in which selected words have been removed) that students are supposed to read within 4 minutes (students are not expected to read the full text). Throughout the text students are expected to fill in missing words by selecting one of three options offered. After 4 minutes students are expected to mark the last word they have read. The test is scored based on the scoring procedure suggested by Schneider, Schlagmüller and Ennemoser (2007) to retain psychometric quality and comparability across grades. Reading speed (RS) is scored as the total words read in 4 minutes. Reading comprehension (RC) was measured as the total score across all missing word items with a correct answer being scored as two points (2), a missing answer being scored as zero points (0) and a wrong answer being scored as minus one point (-1). This scoring scheme allows for comparing students across a wide range of reading comprehension abilities (i.e. students from different grades). For comparability with measures of students' formal-logic thinking and arithmetic abilities both reading speed and reading comprehension scores were z-standardized.

### Cognitive Ability Test

The Cognitive Ability Test by Heller and Perleth (2000) is an adapted version of the Cognitive Ability Test (cogAT) developed by David Lohman (e.g. Thorndike, 1997). The test was designed and validated to assess general cognitive abilities of students from grade 5 to 12 and is available in two forms, A and B (Heller & Perleth, 2000). Each form entails three different subscales, a verbal subscale to assess students' linguistic abilities, a non-verbal one to assess their formal-logic thinking and a quantitative-numeric one to assess arithmetic abilities. Each scale consists of a total of 60 items grouped into grade-specific subsets (grade 5: items 1-25, grade 6: items 6-30, …), which allows for comparing students' cognitive abilities across grades. In this study the non-verbal (KFTN) and quantitative-numeric (KFTQ) subscales were utilized to assess students' formal-logic thinking and arithmetic abilities respectively. Students were administered the subset of items specific to their grade in either form A or B. The obtained data were analyzed using multi-dimensional Rasch analysis. Each form was analyzed independently with the KFTN and KFTQ subscales as independent dimensions. Obtained WLE scores were z-standardized to obtain comparable ability measures for each subscale across test forms and with reading speed and comprehension measures. Psychometric quality of the scales was acceptable (i.e. the items exhibited acceptable model fit with .70 < WMNSQ < 1.30, cf. Wright & Stone, 1979) yielding reliabilities of $\alpha_{N,A} = .73$, $\alpha_{N,B} = .87$ and $\alpha_{Q,A} =.75$, $\alpha_{Q,B} =.70$ for students' WLE estimates.

### *Analysis*

The appropriate procedure to evaluate the influence of background variables such as general cognitive abilities on measures of student test achievement is to use a Rasch Background Model (see for example Rost, Walter, Carstensen, Senkbeil, & Prenzel, 2004). A Rasch Background Model is an extension of the Rasch Model (Rasch, 1980; Wright & Stone, 1979). In comparison to the Rasch Model the Rasch Background Model incorporates a regression of student achievement measures on one or more covariates (i.e. the background model). The Rasch Background Model represents a latent variable modelling approach and corresponds to a structural equation model with categorical indicators. When using a Rasch Background Model, student achievement measures are  based both upon the correctly answered items and their difficulties and on the covariates. This procedure results in an enhanced estimation of student achievement measures. Additionally, the influence of covariates upon student achievement measures can be determined (Rost et al., 2004).

We estimated measures of students' energy understanding based on their responses to the Energy Concept Assessment (ECA) items using a Rasch Background Model. In doing so, we included measures of students' linguistic abilities (i.e. reading speed, RS, and reading comprehension, RC), and students' formal-logic thinking (i.e. non-verbal cognitive abilities, KFTN) and arithmetic abilities (i.e. quantitative-numeric abilities, KFTQ) as well as the amount of teaching on energy (grade) as covariates (see Figure 1). Since students' general cognitive abilities may grow with grade too, we followed a two-step procedure to identify if there is an effect of schooling over maturation. In the first step we included only measures of students' general cognitive abilities (KFTN, KFTQ, RS, RC) in the background model. In the second step we added the grade as well as interactions between grades and covariates. Students' grades were coded into two dummy variables (grade 6: G1=0, G2=0; Grade 8: G1=1, G2=0; grade 10: G1=1, G2=1; cf. Senkbeil & Wittwer, 2004) to allow us to evaluate the effect of students' grades on the change of students' energy measures separately for grade 6 and 8 as well as grade 8 and 10. Interactions were created by multiplying the respective covariate with each of the two dummy variables (e.g. KFTN*G1 and KFTN*G2). We aimed to determine if students' energy understanding as measured by the ECA in addition to maturation depends on schooling. Thus, we examined if the background model created in the second step fits the data significantly better than the one created in the first step. Subsequently we examined significance and size of the effect of students' grade over students' general cognitive abilities. This procedure is the standard procedure when investigating fixed effects (i.e. grade) over random effects (i.e. reading speed) in (latent) mixed modelling e.g. Bates, Maechler, Bolker & Walker, 2014) and compares to classical step-wise regression.

statistic is asymptotically distributed as a chi-squared random variable).

The results for the regression of students' energy understanding measure on the covariates (i.e. reading speed, reading comprehension, quantitative-numeric and non-verbal abilities and grade) are shown in Table 2. We found the effect of students' quantitative cognitive ability (KFTQ) on students' energy understanding measure to be a significant 0.173 logits. Since all covariates except grade were z-standardized that means, an increase of one standard deviation in the students' quantitative cognitive ability across the whole sample leads to an increase of 0.173 logits in the students' energy understanding measure. The effect of students' nonverbal cognitive abilities (KFTN) was found to be significant as well, yet, with a 0.045 logits, was limited in comparison to students' quantitative cognitive abilities. With respect to students' linguistic abilities, we found reading comprehension (RC) to affect students' energy understanding measures by 0.150 logits per standard deviation. In contrast, the effect of reading speed (RS) was nearly negligible at about -0.006 logits.

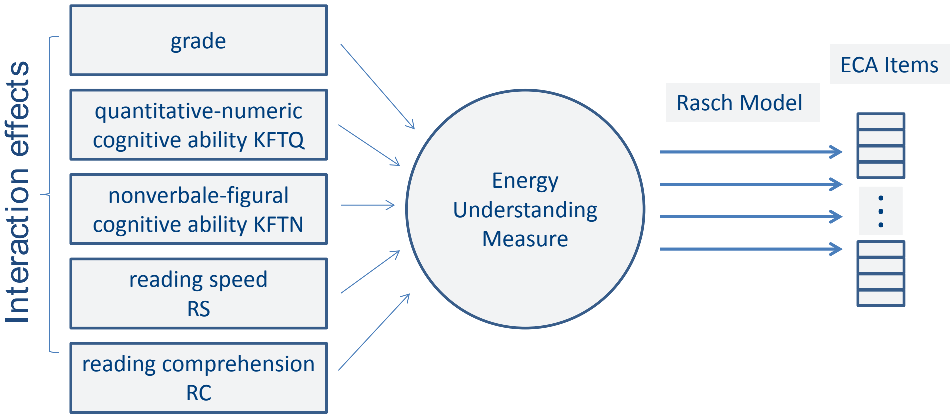

Figure 2. Rasch Background Model

## Results

The analysis we performed to explore the effect of cognitive abilities (i.e. maturation) over grade (i.e. schooling) on students' energy understanding measures yielded a significantly better fit of the second model (including the effect of schooling and maturation) over the first model (including only the effect of maturation). (Likelihood-Ratio-Test $\chi^2$= 107.56, df = 10, p < .001; see Table 1. The Likelihood ratio test compares two models, the simpler model is a special case of the general model and has fewer parameters than the more complex general model; the test

Table 1. Model fit parameters (lower values indicate better fit)

| | deviance | AIC | BIC | cAIC |
|---|---|---|---|---|
| Model 1 | 36270.82 | 36516.82 | 37196.54 | 36534.43 |
| Model 2 | 36163.26 | 36429.26 | 37164.24 | 36449.96 |

Regarding the effect of energy teaching on student' energy understanding measures, a significant difference between 6th grade students average ability (of -.904 logits) and 8th grade students of 0.175 logits can be observed. The difference between 8th grade and 10th grade students was significant too at 0.344 logits, that is, the average energy understanding measure for 8th grade students is about -0.729 logits, and for 10th grade students about -0.385 logits.

Table 2. Regression coefficients of Rasch Background Model

| | Intercept | KFTQ | KFTN | RS | RC | G1 | G2 | G2*KFTQ[1] | G2*KFTN[1] |
|---|---|---|---|---|---|---|---|---|---|
| Regression Coefficient | -.904 | .173* | .045* | -.006 | .150* | .175* | .344* | .115* | .157* |

[1]Only significant interaction effects are reported; * $p < .05$

Interaction effects were mostly negligible. The only noticeable effect was observed for students' quantitative-numeric and non-verbal abilities in 10th grade. In 10th grade students' quantitative-numeric abilities had an effect of .115 logits and non-verbal abilities had an effect of .157 logits on measures of students' energy understanding.

## Discussion

In this study we demonstrated that students' general domain-unspecific cognitive abilities have a noticeable effect on students' achievement on an energy assessment. This is well in line with the literature, which suggests that students' general cognitive abilities play a major role in students' achievement when solving domain-specific problems (e.g. Baumert, 2009; Helmke & Weinert, 1997; Weinert & Helmke, 1995). We found in particular that students' reading comprehension, as well as their arithmetic and formal-logic thinking abilities to be related to their achievement on the energy assessment. The effect of students' reading comprehension was observable across all grades and expected as the energy concept assessment like all (paper-and-pencil) concept assessments required a particular amount of careful and thorough reading for identifying the correct answering option (cf. Neumann et al., 2013, see also Baumert, Klieme, Neubrand, Prenzel, Schiefele & Schneider, 2001 or Leutner et al., 2004). In PISA 2000 the correlation between students' reading ability and science achievement was for example r = .89 (Adams & Wu, 2002). The effect of students' arithmetic abilities was comparable to the effect of students' reading comprehension across all grades and was even larger for students from grade 10. Whereas reading comprehension has a substantial effect on students' achievement on the energy assessment, the results show a non-existing impact of the reading speed. This could be an artefact of the ECA study.

Students' formal-logic thinking abilities had a significant, but negligible effect on student achievement in all grades, but grade 10. In grade 10, students' formal logic thinking had a similar effect as students' arithmetic abilities and reading comprehension. The relations of both students' arithmetic and formal-logic abilities to their understanding of energy were expected as energy-related problems usually require quantitative thinking (e.g. considering different amounts of energy in different forms) and abstract thinking (e.g. when modeling phenomena based on the principle of energy conservation). Even the growing effects of students' arithmetic formal-logic thinking and arithmetic abilities from grade 6 to grade 10 were expected as the literature suggests a growth in students' general cognitive abilities over time (e.g. Becker, Lüdtke, Trautwein, Köller & Baumert, 2012), which should result in a higher student achievement.

Despite general cognitive abilities having a considerable effect on student achievement, we still find an additional effect of the amount of teaching on energy on student achievement. While we did not directly measure the amount of teaching, in our case students' grade served as a good proxy for the amount of energy teaching. This is because the mandatory curriculum puts a particular focus on energy in middle school and students at the end of grades 6, 8, and 10 are to have learned about the same ideas and have received comparable amounts of teaching. In fact, we find the accumulated effect of students' grade to be larger than the cumulative effect of students' general cognitive abilities.

The finding that students with higher general cognitive abilities (i.e. more mature students) tend to exhibit a higher understanding of energy suggests that maturation plays a role in students' learning about energy that cannot be neglected. In particular the influence of cognitive abilities is larger in higher grades (i.e. for more mature students). Students at higher grades seem to use their cognitive abilities in a more appropriate way as students in lower grades. This result could be an indication, that e.g. younger students can get the idea of energy forms as different manifestations of energy, because an extensive development of arithmetic abilities is not necessary for an understanding of this aspect of energy. Whereas the understanding of more complex aspects of energy – like energy conservation – needs a more sophisticated development of arithmetic abilities. Therefore, a deep understanding of aspects of energy, that need more distinct arithmetic and formal-logic abilities (like understanding energy conservation, that requires a systemic approach), can be expected only from students of higher grades.

However, the larger accumulated effect of grade than the accumulated effect of cognitive abilities suggests that schooling plays the more important role than maturation in students' learning about energy. This points out the important role of the curriculum.

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