Please cite as:

Schwichow, M., Osterhaus, C., & Edelsbrunner, P. A. (in press). The relation between the control-of-variables strategy and content knowledge in physics in secondary school. *Contemporary Educational Psychology*.

This is a preprint of the last submitted author version.

**The relation between the control-of-variables strategy and content knowledge in physics in
secondary school**

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Acknowledgments

We thank Steve Croker for helpful comments on a draft of this paper, and Simon Christoph for his support in designing this study, assessments, and analyses.

Highlights:

- We analyze a large cross-sectional dataset using latent variable- and latent profile analyses

- Science content knowledge predicts performance in the control-of-variables strategy
- Students plan, interpret and identify controlled experiments before they understand the indeterminacy of confounded experiments
- Lower secondary students do not understand the indeterminacy of confounded experiments

Abstract

The control-of-variables strategy (CVS) is considered a hallmark in the development of scientific reasoning. It holds that informative experiments need to be contrastive and controlled. Prior evidence suggests that CVS is connected to the acquisition of science content knowledge. In a cross-sectional study involving 1,283 high school students (grades 5 - 13), we investigate whether students' mastery of CVS is related to their science content knowledge in physics. A latent variable model indicates that CVS is substantially associated with students' science content knowledge, even when controlling for common effects of general reasoning abilities. Substantial differences in students' CVS skills and their science content knowledge exist between the lower grade levels in secondary school when students receive physics education. A latent profile analysis shows that the most difficult aspect of CVS is understanding the impact of confounding. This sub-skill emerges in late secondary school and it requires that students master more procedural sub-skills of CVS. These findings indicate that CVS and science content knowledge are closely related within secondary school science contexts. In addition, the findings emphasize that students show various distinct patterns of CVS skills. The identified skill patterns can inform researchers and science educators about the CVS skills that students typically show and thus can be utilized in inquiry activities in different school grades, while the CVS skills students are lacking might be trained in focused interventions.

Keywords: control-of-variables-strategy; content knowledge; secondary school; structural equation modeling; latent profile analysis

Introduction

Scientific experiments allow reasoners to draw conclusions with respect to the causal standing of single variables by contrasting conditions that differ only with respect to the variable whose causal status is under investigation. The critical skills required for designing and interpreting such controlled experiments are brought together under the term “control-of-variables strategy” (CVS; Chen & Klahr, 1999). CVS is an interdisciplinary strategy for designing and interpreting empirical data about causal relations, as controlling variables is crucial for the validity of experiments in all natural and social sciences. The logic of controlling variables is not based on any disciplinary knowledge because it is related to the general idea of causality and not to specific disciplinary models or methods (Woodward, 2003). In contrast to the interdisciplinary nature of CVS, the results of numerous studies show that people’s skills in controlling variables are closely related to their disciplinary knowledge regarding the context of the experiments (Schauble, 1990; Schalk, Edelsbrunner, Deiglmayr, Schumacher, & Stern, 2019; Schwichow & Nehring, 2018). Knowledge about which aspects of the CVS construct are closely related to students’ science content knowledge is the basis for understanding this relation between CVS and content knowledge and can inform the design of intervention strategies. Therefore, the present cross-sectional study investigates the relationship between four CVS aspects and science content knowledge.

Theory

CVS: Sub-skills, Relevance in Education, and its Development

According to the fundamental notion of causality in science, variable X has a causal effect on a variable Y when there is an intervention that changes the value of X, and when applying this but no other intervention results in a change of the value of Y (cf. Woodward, 2003). In consequence, controlling variables in experiments is directly related to causality because it ensures that the

intended variable and no other variable has a causal effect. Controlling variables is important in many different operations regarding the design, interpretation and evaluation of experiments. A comprehensive definition of CVS by Chen and Klahr (1999) summarizes different procedural and logical aspects of controlling variables in experiments. According to this definition, CVS comprises the abilities to (a) plan and create experiments whose conditions differ only with respect to a single contrasting variable, and to (b) identify confounded and unconfounded experiments. In addition, CVS requires that reasoners understand its logic, which involves the ability to (c) make appropriate inferences from the results of unconfounded experiments (e.g., the understanding that inferences about the causal status of the variable being tested are warranted) and the ability to (d) recognize the inherent indeterminacy of confounded experiments (Chen & Klahr, 1999). A full understanding of CVS thus includes four sub-skills: (1) *planning* and *creating* controlled experiments (PL), (2) *identifying* confounded and unconfounded experiments (ID), (3) *interpreting* the outcome of controlled experiments (IN), and (4) *understanding* that only inferences of indeterminacy can be drawn from the results of uncontrolled experiments (UN).

Because of its important role in science, CVS is included in many current science curricula and standards (e.g. USA: NGSS Lead States, 2013; England: Department for Education 2014; Switzerland: D-EDK, 2016; Germany: Wellnitz et al., 2012). CVS is seen as a crucial skill that students need to possess in order to benefit from inquiry-based learning in science education (Abd-El-Khalick et al., 2004). Mastery of CVS contributes to successful inquiry learning, because it enables students to conduct their own informative experiments (Edelsbrunner, Schalk, Schumacher, & Stern 2018; Stender, Schwichow, Zimmerman, & Härtig, 2018). In addition, mastery of CVS is a prerequisite for the development of more advanced scientific-reasoning skills,

such as multivariate causal reasoning and complex problem solving (Kuhn, Iordanou, Pease, & Wirkala, 2008; Wüstenberg, Greiff, & Funke, 2012; Zimmerman, 2000, 2007).

Mastery of CVS in less complex tasks with a limited number of variables that are easy to identify has been shown to emerge already in elementary school (Bullock & Ziegler, 1999; Osterhaus, Koerber, & Sodian, 2016), and it is related to children's meta-conceptual understanding of experimentation and of the nature of science (Osterhaus, Koerber, & Sodian, 2017). Although a rudimentary understanding of CVS has been demonstrated in children as young as 6 (Koerber & Osterhaus, 2019) and precursors of CVS are found in preschool children (Piekny & Maehler, 2013; Sodian, 2018; Sodian, Carey, Grosslight, & Smith, 1992), mastery of CVS remains to be difficult even for adults (Bullock, Sodian, & Koerber, 2009).

Available evidence on CVS in secondary school comes from a longitudinal study that investigated the development of CVS skills from age nine to 23 (Bullock et al., 2009). The participants ($N=132$) were asked to produce controlled experiments (planning sub-skill PL) to test a given hypothesis and to choose a controlled experimental comparison out of a selection of controlled and confounded experiments (identification sub-skill ID). The findings show that at an age of 9, already 40 % of the participants can choose controlled experiments while at the same age only a few can create controlled experiments. The ability regarding both sub-skills increases dramatically until the age of 23 when the identification tasks are solved by 90 % and the planning tasks by 80 % of the participants. However, the ability to plan controlled experiments increases much slower and at the age of twelve only 38 % of the participants solved the planning tasks. Although this finding demonstrates that adolescence is a crucial period for the development of profound CVS skills, they are limited, as the study did not investigate the development of the interpreting (IN) and understanding (UN) sub-skills. (Bullock et al., 2009).

CVS and Science Content Knowledge

Individual differences regarding CVS skills in adulthood might be caused by limitations in individuals' science content knowledge (Koslowski, 1996; Kuhn, 2009). Science content knowledge is defined here as knowledge about scientific concepts and facts. Examples of science content knowledge include knowledge about Newtonian mechanics and electrical circuits in physics, genetics and evolutionary theory in biology, or molecular structure and atomic numbers in chemistry. Researchers often investigate the development of CVS and science content knowledge separately of each other (Klahr, Zimmerman, & Jirout, 2011). However, in typical inquiry situations, CVS is embedded in contexts that require mastery of CVS *and* science content knowledge within the context of inquiry. Theoretical models (Klahr & Dunbar, 1988) and empirical evidence (Schauble, 1990; Schalk, Edelsbrunner, Deiglmayr, Schumacher, & Stern, 2019) indicate that the development of CVS and science content knowledge may indeed be vigorously intertwined.

Observational evidence for the interplay between CVS and science content knowledge stems from lab studies with fifth- and sixth-graders (Schauble, 1990, 1996): While working on a belief revision task, students' knowledge about causal relations influenced their experimentation strategies; at the same time, students' experimentation strategies influenced their acquisition and revision of knowledge about causal relations. For example, in finding out which variables influence the speed of race cars, children who applied valid experimentation strategies, such as CVS, increased their science content knowledge relative to those who applied limited heuristics in their experimentation (Schauble, 1990).

Koerber and Osterhaus (2019) found that children's science content knowledge in physics is related to their scientific reasoning skills (incl. their experimentation skills) already in

kindergarten, even before children enter formal education. This suggests that CVS and science content knowledge may predict each other's development and acquisition from early on. The influence of CVS on the acquisition of science content knowledge can be illustrated with the following example: Consider children who find out about floating and sinking phenomena. They receive cubes with different sizes made up of different materials such as wood, styrofoam, and metal. Children who master CVS will try out whether a smaller and a bigger cube made up of wood float or sink in water. When they observe that both cubes float, they will correctly infer that size does not make a difference. Children who do not master CVS might, in contrast, vary size and material at the same time and unsystematically experiment with cubes of different sizes and materials. These children might infer either that it is the size or both the size and the material which impact whether or not an object floats (which of course is incorrect).

Varying one characteristic of the object at a time supports children's content knowledge acquisition about the influence of characteristics such as object size and weight on floating ability (Hardy, Jonen, Möller, & Stern, 2006). Floating and sinking is a domain that is present in everyday life; children who already possess knowledge about CVS might be better equipped to learn about the causal relations underlying these phenomena. This assumption is supported by a recent study showing that first- to sixth-graders' knowledge of CVS is a substantial predictor of children's science content knowledge development when they receive inquiry-based education on floating and sinking (Edelsbrunner et al., 2018).

Evidence for the influence of science content knowledge on the development of CVS, in turn, comes from a study by Wagenveld, Segers, Kleemans and Verhoeven (2015) who found that fourth- and sixth graders' science content knowledge is predictive for their CVS skills before undergoing training, and for their ability to transfer newly acquired CVS skills after the training.

Furthermore, van der Graaf, Segers, and Verhoeven (2018) gave preschool children a CVS task twice - one at 4 years of age and another at 5. The science content knowledge of the children about four topics in physics and biology was not only associated with children's CVS skills at the first assessment, but also it predicted children's further development of CVS within one year. These results emphasize the mutual impact of CVS and science content knowledge in childhood. However, at later educational stages, particularly beyond middle school, evidence on CVS is sparse (but for one study see Bullock, Sodian & Koerber 2009).

Students' experimentation and scientific-reasoning skills have been related to their general cognitive abilities, including their executive functions (Kwon & Lawson, 2000; Osterhaus et al., 2017; van der Graaf et al., 2018), language abilities (Mayer, Sodian, Koerber & Schwippert, 2014; Koerber, Mayer, Osterhaus, Schwippert & Sodian, 2015; Koerber & Osterhaus, 2019), and intelligence and general reasoning abilities (Mayer et al., 2014; Koerber et al., 2015; Koerber & Osterhaus, 2019). Therefore, studies that investigate the relation between CVS and science content knowledge should control for general reasoning abilities, ensuring that the mutual association is not a consequence of the mutual influence of more general skills. The association between scientific reasoning and science content knowledge is independent of the common influence of intelligence and language abilities in 6-year-old children (Koerber & Osterhaus, 2019), but whether this is true for the association between the two constructs in older students is not clear.

The Present Study

Detailed knowledge about the development of the four CVS sub-skills in secondary school can inform science education practice as it highlights which skills are typically developed in different school grades and therefore can be utilized in inquiry activities. Information about which skills are typically unknown also accentuates what should be the focus of instructional

interventions at a specific age or educational level. Evidence of the relation with content knowledge might inform about the alignment of the teaching of inquiry skills and of science content knowledge. In addition, evidence regarding a relation between science content knowledge and CVS might be one explanation of intra- and interindividual differences in CVS skills.

The current study examines when all four CVS sub-skills first emerge in secondary school, and how these skills are related to students' science content knowledge. Based on Schauble's (1990, 1996) observational findings and correlational findings from childhood (van der Graaf et al., 2018; Wagenveld et al., 2015; Edelsbrunner et al., 2018), we expect a significant correlation between CVS and science content knowledge in secondary school that is independent of students' general reasoning abilities (see Koerber & Osterhaus, 2019). Adolescents' mastery of identification- and planning- tasks seems to fully emerge in adolescence (Bullock et al., 2009), and so we predict that secondary schoolers' achievement on these tasks will significantly improve in higher grades. Understanding the indeterminacy of confounded experiments is the most difficult CVS sub-skill (Schwichow, Christoph, Boone, & Härtig, 2016); therefore, we assume that students master the PL-, ID-, and IN-sub-skills before they understand the indeterminacy of confounded experiments (UN-sub-skill). Our research questions and hypothesis are:

Research question 1 (RQ 1): How are the four CVS sub-skills related to each other?

Research question 2 (RQ 2): When do the four CVS sub-skills emerge and which cross-sectional differences are visible across school grades?

Hypothesis 2.1: Students' performance on identification and planning tasks is higher in higher grades.

Hypothesis 2.2: Students master the planning, identification and interpretation sub-skills before they understand the indeterminacy of confounded experiments.

Research question 3 (RQ 3): Are the four CVS sub-skills related to students' science content knowledge?

Hypothesis 3: There is a positive relation between CVS and science content knowledge that is independent of students' general reasoning abilities.

To answer our research questions, we assessed students' CVS skills and content knowledge in a large cross-sectional sample of secondary school students (grades 5 to 13) from Germany. Within this sample, we pose CVS tasks on students embedded in physics contexts that are part of the local secondary school physics curricula during those school grades. This allows examining the degree to which the science content knowledge students acquire in secondary school is related to the mastery of CVS within the respective contexts of scientific inquiry.

Method

Sample

Students from three secondary schools (*Gymnasium* in Germany) in rural areas of northern Germany (state of Schleswig-Holstein) participated in this study. The German *Gymnasium* is a secondary school for students approaching a university entrance exam and incorporates grade 5 to 13 (age 10 to 19). The students from these schools are generally academically medium to high achieving, as students with lower academic abilities (according to the final elementary school reports) cannot enter these schools. Permission to conduct this study was obtained from the State Ministry of Education and from the school principals, as is common procedure in the country under study. We did not collect data that allowed to identify participants. All students from grade 5-13 of the three schools agreed to participate in the study (see Table 1 for distribution of students over grade), which yielded an initial sample of 1,425 students.

Due to technical issues with the computers used for the assessments or the assessment software platform, the data from 131 students had to be excluded from subsequent analyses. The data of 11 additional students were excluded because they failed to complete at least one item from each CVS sub-skill. The final sample on which the analyses reported here are based on hence consisted $N = 1,283$ students (52% female, 48% male), with a mean age of 13.80 years ($SD = 2.44$). The slightly higher percentage of female students is typical for Gymnasiums in the state of Schleswig-Holstein (52.63% of students are female) and for Germany in general (53% of students are female; Statistical office of Hamburg and Schleswig-Holstein, 2018). The social and ethnic background of the students from the respective area of Germany can be described as predominantly middle class and of German origin.

Assessment Instruments

Control-of-variables strategy. To assess students' CVS skills, we adopted and expanded the CVS Inventory (CVSI; Schwichow et al., 2016). The original CVSI consists of 23 multiple-choice items embedded in middle school physics contexts of heat and temperature, and electricity and electromagnetism (further referred to as electro/magnetism). The 23 items of the CVSI instrument cover the identification (ID), interpretation (IN), and understanding (UN) sub-skills of CVS as defined by Chen and Klahr (1999). We expanded the original version of the CVSI because (1) it lacks items belonging to the sub-skill of planning controlled experiments (PL), (2) the existing items are not equally distributed over all sub-skills, and (3) measures from the IN ($\alpha = 0.60$), ID ($\alpha = 0.76$) and UN subscales ($\alpha = 0.68$) demonstrated rather moderate internal consistency in prior research.

The revised version of the CVSI consists of 48 multiple-choice items: 12 items for each of the four CVS sub-skills. Every item has one correct answer and three distractors, so that the probability of correctly answering a question by chance is about 25%. The items cover the same physics contexts of heat and temperature (24 items) and electro/magnetism (24 items) as the original CVSI. Both contexts are mandatory topics in physics classes from grade seven to ten in the relevant parts of Germany (Ministry of Education, Science, Research, and Culture of Schleswig Holstein, 2014).

The newly developed planning items (PL) start with a short story about a protagonist who wants to test a specific hypothesis about a causal relationship. An example item of this type is presented in Figure 1. Students are asked to plan an experiment for testing the hypothesis by choosing the levels of two independent variables (e.g. copper wire versus iron wire and small versus large battery). After students have chosen the variable levels by clicking on a button next to the name of the variable level, a graphical representation of the experiment appears on the screen. The representation shows all variable levels selected by the students, and the physically correct effect on the dependent variable (e.g., brightness of a light bulb depending on the wire material). Students can modify their experimental set-up as often as they want to before they submit their answer and start with the next item. In contrast to the items on the remaining sub-skills, planning items (PL) only have two independent variables because the probability of answering a planning item correctly by chance would drop to 1% for items with three independent variables with two levels each. The revised version of the CVSI was implemented as an online survey because this format allows the construction of interactive planning items (PL).

The identification items (ID) are similar to the planning items as they also present short stories that end with a hypothesis about a causal relationship. Afterwards, students have to select

one correct experiment from one of four graphically presented experiments. Only one experiment shows a controlled experiment and is therefore correct. The distractors show confounded experiments with two or three variables changed and non-contrastive experiment that contrasts two identical experimental set-ups. For each ID item, the order of answer options was random. An example of an ID item is presented in Figure 2.

The items for the CVS sub-skill interpreting (IN) and the items for the sub-skill understanding (UN) have a highly similar structure (see Figure 3). Items of both types start with a drawing that shows the outcome of an experiment. Students are then asked to interpret the presented experimental outcome. The only difference between the two item types is that interpreting (IN) items presents the outcome of controlled and valid experiments. The understanding (UN) items consider the outcome of confounded and thus invalid experiments. For IN items, students thus have to draw appropriate inferences from a controlled experiment. For UN items, students have to decide that the presented experiment is confounded and to recognize that they cannot draw a valid conclusion from the presented outcome. The four response options for the IN and the UN items are standardized and are always presented in the same order. The response options are:

- (1) Variable X has an impact on the outcome of the experiment.
- (2) Variable Y has an impact on the outcome of the experiment.
- (3) Variable X and variable Y have an impact on the outcome of the experiment.
- (4) The experiment does not allow any valid conclusion.

Evidence for the validity of CVSI measures comes from studies that utilized items from the instrument. For example, Authors (2016a) used test booklets with 12 CVSI items in an intervention study on CVS and found that the items are sensitive to intervention effects. Strong evidence for construct validity are the results of a study that investigates the relation between discriminant

constructs (reading and general reasoning abilities), convergent constructs (students CVS skills in real hands-on tasks and students CVSI measures) on their gains in content knowledge (measured by the same test as in this study). The results of a structural equation model that tests all relations between the constructs yielded that students' learning gains were predicted solely by their CVS hands-on skills, which in turn depended on their measures on the CVSI. Reading and general reasoning skills did only have small direct effects on CVSI measures and the hands-on skills (Author, 2018). This finding indicates evidence for the valid interpretation of CVSI scores, as CVS is theoretically a strategy to construct valid experiments from which new knowledge can be constructed. Arguments for content validity are that the contexts of the CVSI items are representative for secondary school curricula in the state of Schleswig-Holstein, and that the items cover all relevant sub-skills of the CVS construct.

Science content knowledge. Students' science content knowledge about heat and temperature and electro/magnetism was assessed with 24 single-select and 7 multiple-choice items. These topics were assessed because they also provided the context for the items on the CVS assessment. However, knowledge about these topics was not strictly required in order to solve the tasks on the CVS assessment. The single-select items ask students about the causal relation between the independent and dependent variables utilized in the CVS test (e.g., "Do thinner wires get warmer than thicker wires?", correct answer: yes). Twelve of the single-select items cover topics from heat and temperature and 12 cover electro/magnetism. The multiple-choice items asked students about facts (e.g., "At what temperature does ice melt?") and their understanding of basic concepts (e.g., "Why do we feel cold after stepping out of a bathtub?") in both areas of physics. All multiple-choice items had one correct answer option and three distractors that were constructed on the basis of student replies to open-ended questions. Four of the multiple-choice items covered

questions about heat and temperature and three about electro/magnetism. The science content knowledge test was embedded in the same online survey as the CVS test.

Evidence for validity of the content knowledge scores comes from a study by Stender et al. (2018) which reports significant relation between learning gains in content knowledge measured by the same instrument and the quality of students' inquiry activities. A further argument for the validity of the scores comes from a reanalysis of three independent data sets on the relation of CVS and content knowledge in biology, chemistry and physics. The findings of this analysis show for all three domains the same relation between CVS and CK (Author, 2018). In the present sample, convergent validity of students' content knowledge scores is indicated by moderate associations with their verbal reasoning ($r = .34$), figural reasoning ($r = .32$), and numeric reasoning ($r = .36$) scores. These correlations are in the same range as in previous studies utilizing the instrument and the same general reasoning scales (Authors, 2018, Stender, et al. 2018).

Reasoning abilities. In order to control for students' general reasoning abilities, their numeric, verbal, and figural reasoning abilities were assessed by three subscales from a standardized German intelligence test (Kognitiver Fähigkeits Test, KFT; Heller & Perleth, 2000). Each scale consists of 20 single-select items of which the five easiest are replaced by five more difficult ones when it is presented to students from one school grade higher. Students' answers on the partially overlapping scales from the different school grades can be linked and analyzed by item response modeling (Rasch scaling). The KFT test is a standard diagnostic instrument in Germany. The handbook reports numerous sources of evidence for the valid and reliable interpretation of test scores including test-retest reliability and substantial correlation with alternative intelligence tests and school achievement (Heller & Perleth, 2000). For time reasons, each student worked on one of the three subscales. Thus, one third of the school classes received

the numeric reasoning scale (scale Q2; number series, Warm likelihood reliability estimate: .75), another third on the verbal reasoning scale (scale V2; semantic categories, reliability: .64), and the remaining third the figural reasoning scale (scale N2; figure analogies, reliability: .74). We ensured that the reasoning scales were equally distributed over grades and schools by systematically allocating classes to the reasoning scales. This way, data from about a third of the students was obtained for each reasoning scale.

Procedure

The data collection took place during a regular school lesson of 45 minutes in the computer rooms of the schools. All data collection was done via an online survey. Students were presented an informed consent sheet before they had to provide their gender and age. Then, they answered items of one of the three reasoning scales. Whole classes of students were randomly assigned to work either on the figural reasoning, the verbal reasoning, or the numeric reasoning scale. Next, students worked on the science content knowledge items. They had to reply to all science content knowledge items before they started working on the CVS test.

The 48 items of the CVS test were presented in a fixed order, starting with a planning item (PL) followed by an identification (ID), an interpretation (IN) and an understanding item (UN) that all had the same context (e.g. melting of ice). After students submitted the answer to an item, they could not go back and change it. We alternated the contexts so that four items from a heat and temperature context were followed by four items within the context of electro/magnetism. In order to avoid a systematic impact of the context, we implemented the CVS test in a matrix design. That is, students received twelve different subsets of the 48 items (12 experimental contexts a one item for every sub-skill), all starting with a planning item but within a different context. Each subset consisted of 24 items. In the instructions, it was emphasized that students should finish these 24

items, in order to ensure that the matrix design yielded a similar percentage of students answering each of the items. Afterwards, the students could continue answering further items until the official lesson time was over. Thus, all students had to answer at least 24 CVS items but those who finished before the end of the 45-minutes test time were asked to answer as many additional CVS items as possible. Using this procedure, it was possible to gather more data while being able to accommodate for differences in processing time between students.

Data Scaling, Reliability Estimation and Statistical Models

To scale students' achievement on the four CVS sub-skills, science content knowledge, and the three reasoning scales, we used Rasch scaling in the Mplus software package version 7.11 (Muthén & Muthén, 2012). Person ability estimates yielded from this scaling procedure were used as indicator variables in all further analyses. The measurement model underlying the CVS and science content knowledge scales was tested in a multidimensional Rasch model. After removing three of the science content knowledge items and one identification - as well as one understanding-item that showed cross-loadings - the measurement model of the five scales showed excellent fit (Hu & Bentler, 1999, $\chi^2_{2755} = 4106.56$, $p < .001$, $RMSEA = .02$, $CFI = .96$). These three science content knowledge and two CVS items were removed from all further analyses. A measurement invariance analysis shows strong invariance of the four sub-skills and indicate that the Rasch scaling functioned similarly across school grades (Table 2). The four CVS sub-skills did not exhibit any topic-specificity, as indicated by correlations of 1 across the two topics for each sub-skill. Consequently, differences between the two physics topics were not taken into account in the main analyses.

For reliability estimates of the focal study variables, we used the internal consistency index Omega (ω) in the *R* package *psych* (Revelle, 2017). The ω index yields a less biased reliability

estimate than the commonly used Cronbach's Alpha (Dunn, Baguley, & Brunsten, 2014). Cronbach's Alpha makes the unrealistic assumption that all items have the same loadings, which in most cases leads to underestimation of the real reliability. Omega is an index of internal consistency that does not make this assumption and therefore is generally at least as precise as Alpha, and often more precise (Dunn et al., 2014). In all analyses, we modeled CVS, science content knowledge, and reasoning abilities as latent variables. In this way, all model estimates were corrected for measurement error. For examining model fit, we relied on common rules for fit indices ($RMSEA < .06$, $CFI > .95$, $SRMR < .09$; Hu & Bentler, 1999). Additionally, we looked into residual correlations to find potential sources of misfit (Heene, Hilbert, Draxler, Ziegler, & Bühner, 2011). To correct for potential deviations from normal distributions, robust maximum likelihood estimation was applied, which corrects chi-square and standard error estimates for deviations from normality. We applied full-information maximum likelihood estimation to use information from participants with partially missing data. We only indicate statistical significance for model parameters testing our focal research questions because statistical significance loses its information value when it is applied to exploratory analyses (Rubin, 2017; Wagenmakers, Wetzels, Borsboom, van der Maas, & Kievit 2012). For readers interested in additional specific details about analyses and results, supplementary materials including full data files, model specifications and outputs are available from <http://bit.ly/ckandcvs>.

In order to examine the structure of CVS, we applied two types of statistical analyses, of which one is considered *variable-centered* and the other *person-centered*. The reason for combining two statistical approaches was that they mutually inform each other in answering our research questions. First, we applied a confirmatory factor analysis. This variable-centered analysis helps investigating whether CVS can be modeled as an overarching trait across the four sub-skills.

It is thus a variable-centered analysis, because it aims at representing structural relations between variables. If this analysis shows misfit, this would indicate that the pattern of intercorrelations between the four CVS sub-skills is not in accordance with the assumption of a common skill underlying achievement on the four sub-skills.

The second type of analysis was a person-centered approach, namely, a latent profile analysis (Hickendorff, Edelsbrunner, McMullen, Schneider, & Trezise, 2018). This analysis does not model a single CVS skill that overarches the four sub-skills, but rather searches for subgroups of students who show different answer patterns across the four sub-skills (Harring & Hodis, 2016). It has a significant advantage over analyses based on sum scores (e.g., Chen & Klahr, 1999), Rasch modeling (e.g., Schwichow et al., 2016) or confirmatory factor analysis-approach. Specifically, these methods assume linear patterns in students' achievement across the four sub-skills and that across all students these skills adhere to the same difficulty pattern (e.g., students who solve more difficult items also solve less difficult items) and thus are ill-equipped for detecting non-linear patterns in students' CVS sub-skills. Latent profile analysis on the other hand can be applied to model both linear and non-linear patterns and can reveal complex patterns across the four sub-skills that would stay hidden in the former types of analyses (Edelsbrunner & Dablander, 2019; Hickendorff et al., 2018). This analysis therefore can provide additional information over and beyond the confirmatory factor analysis. We applied a latent profile analysis in order to test our assumption that lacking any of the three other sub-skills undermines developing the sub-skill of understanding indeterminacy. Based on this expectation, we predicted that students in profiles with high levels of the UN sub-skill would also exhibit high levels on the remaining sub-skills.

Results

Descriptive Statistics

In a first step, we checked whether students from the three schools differ on the four CVS sub-skills and content knowledge. The results of one-way ANOVAS yield no significant differences between students from different schools (Table 3). Intercorrelations between the main study variables as well as internal consistency estimates are presented in Table 4. The four CVS sub-skills show substantive correlations. However, the correlations between understanding (UN) and the other three sub-skills are weaker than the correlations between the planning (PL), identification (ID), and interpretation (IN) sub-skills. Students' grade level was positively correlated with their CVS sub-skills; again this correlation was weakest for the understanding sub-skill. The distributions of the four CVS skills across school grades are presented in Figure 4. There was a general trend that students' scores increased between the lower school grades (grades 5-9) on the PL, ID, and IN scales, while their skills on the UN scale increased between grades 10 and 11. Students from grade 11 seem to represent a mild outlier in cross-sectional developmental trends, which might be caused by the relatively small sample ($n = 60$) size leading to a less reliable estimate in this grade in comparison to the other grades (between 70 and 211 students).

The Development of CVS and its Relation to Science Content Knowledge

We conducted confirmatory factor analyses to model CVS (RQ 1), its development across school grades (RQ 2), and its relation to students' science content knowledge (RQ 3). To include science content knowledge in the models, we Rasch scaled two item parcels consisting of the items in the heat/temperature (HT) and in the electro/magnetism (EM) topic, respectively. Adding two item parcels allowed estimating a latent variable representing science content knowledge, thereby correcting for measurement error (Little, Cunningham, Shahar, & Widaman, 2002). We applied

the same strategy to include students' general reasoning abilities in the models, building three parcels for each of the three reasoning scales.

We first examined whether students' achievement on the four CVS sub-skills can be modeled and represented by an overarching trait (RQ 1). An initial examination of model fit suggested that this model did not provide a sufficient approximation of the correlations between the four sub-skills, as indicated by insufficient fit indices ($\chi^2_2 = 25.45, p < .001, RMSEA = .10, CFI = .99, SRMR = .02$). However, inspection of residual correlations between the four sub-skills that could not be explained by a single overarching trait indicated that the IN- and UN-sub-skills showed an additional correlation going beyond the common CVS-trait. This additional dependency is straightforwardly explained, because the items assessing these two sub-skills have exactly the same structure and answer options. As described in the method section, the two types of items only differ in whether the presented experiment is controlled (IN) or confounded (UN). Thus, it is reasonable to let the residual variance of these two indicator variables correlate. A modified model including this residual correlation showed almost perfect fit ($\chi^2_1 = 0.46, p = .498, RMSEA = .00, CFI = 1.00, SRMR = .00$), indicating that modeling CVS as a single variable provides an adequate representation of the data structure.

Adding students' school grade level to the model indicated that grade level is a strong predictor of the latent variable representing CVS, with a standardized regression weight of $\beta = .64, CI_{90} [.60, .68, 90\% \text{ confidence interval}]$. Thus, students' CVS skills show strong increases across school grades. We then added another latent variable of students' science content knowledge to the model. This final model, with appropriate fit indices of $\chi^2_{11} = 42.46, p < .001, RMSEA = .05, CFI = .99, SRMR = .02$, is depicted in Figure 5. Science content knowledge and grade level correlated strongly, $r = .77, CI_{90} [.73, .82]$. In this model, the predictive value of grade level for CVS skills

diminished towards $\beta = .01$, $CI_{90}[-.17, .15]$. Thus, science content knowledge explains the predictive value of school grade for students' CVS, with a high standardized regression weight of $\beta = .84$, $CI_{90} [.67, 1.00]$. When taking into account students' reasoning abilities, the predictive weight of science content knowledge decreased moderately but remained high at $\beta = .81$ $CI_{90} [.67, .91]$ after controlling for numeric ability, $\beta = .74$ $CI_{90} [.66, .82]$ controlling for figural ability, and $\beta = .74$ $CI_{90} [.48, .99]$ controlling for verbal ability. The reasoning scales are not included in Figure 5 because three separate models had to be set up, one for each of the three subsamples that had received either of the reasoning scales. To summarize, the results from the confirmatory factor analyses indicate that CVS develops substantially across school grades, and this development can be explained by the strong predictive value of students' science content knowledge for CVS, which remains substantial after taking into account students' reasoning abilities.

Developmental Patterns of the CVS Sub-Skills

We conducted a latent profile analysis (LPA), in order to examine our hypothesis that students who master the UN sub-skill also master the other sub-skills (hypothesis 2.2). The LPA, which has been suggested as an informative tool for examining skills related to scientific reasoning (Edelsbrunner & Dablander, 2019), extracts patterns of students' mastery across the four CVS sub-skills. For choosing the best-fitting latent profile model, we relied on the *BIC* criterion and the Vuong-Lo-Mendell-Rubin likelihood ratio test. This test has been shown to be quite reliable in simulations (Nylund, Asparouhov, & Muthén, 2007; Peugh & Fan, 2013). Furthermore, we considered that CVS profiles should each describe at least about five percent of students (Hickendorff, et al. 2018).

The latent profile analysis indicated six subgroups of students with distinct profiles across the four CVS sub-skills. The relative fit indices for the solutions with one to eight profiles are

presented in Table 5. While the solution with seven profiles shows mildly better fit (i.e., lower BIC) than the solution with six profiles, it adds a profile that is not of theoretical interest and only represents about 2% of students, and the likelihood ratio test was not significant. We therefore dismissed the solution with seven profiles in favor of the solution with six profiles. With eight profiles, model convergence could not be reached despite a large number of starting values (1000 initial start value sets of which the 400 most promising were continued with), the BIC increased again, and an additional profile describing just 3% of students arose. Therefore, we also dismissed the solution with eight profiles and continued analyses based on six profiles.

The six profiles, which are depicted in Figure 6, were labeled according to their level and shape (Marsh, Lüdtke, Trautwein, & Morin, 2009). Four of the six profiles differed mostly in level. There was one group of students lacking proficiency on all four sub-skills (“basic proficiency” profile), one showing rather moderate proficiency (“moderate proficiency”), one showing about average proficiency on all sub-skills (“average proficiency”), and one showing high proficiency on all sub-skills (“advanced proficiency”). The fifth and sixth profiles did not just indicate differences between students in level of CVS sub-skills, but differences in shape. That is, these two remaining profiles represented overlapping profiles of students differing in proficiency levels across the four sub-skills. These were the *planning proficiency* profile with students who were below average but exceeded in their ability to plan controlled experiments, and the *control proficiency* profile with students showing high proficiency on three sub-skills (identification, planning, interpretation) but lacking proficiency on the UN skill. Thus, these students have acquired the skills necessary for setting up and interpreting controlled experiments, but they lack deep understanding of the consequences of confounding. Regarding the frequencies of the profiles (see Figure 6), about one quarter of the students was estimated to belong to the *average proficiency* profile, whereas only

about 7% to the *planning proficiency* profile, with the other profiles spread about evenly between these numbers.

Importantly, there was a pattern with respect to the UN sub-skill that supports our prediction. That is, students in five of the six profiles all show a similarly low level of proficiency on the UN sub-skill. Only in the full-proficiency profile, in which students were generally proficient on all sub-skills, were they also highly proficient on the UN sub skill. This proficiency pattern is in accordance with our assumption that mastery of the UN sub-skill follows but does not precede mastery of the other sub-skills.

Next, we added again students' school grade and the latent variable representing their content knowledge to the model, in order to examine whether and how students showing the different profiles differ on these variables. Adding the covariates directly into the model did almost nothing to change the level and shape patterns of the CVS profiles, which sometimes happens, particularly in smaller samples (Hickendorff et al., 2018). Similar to the confirmatory factor analysis-based model, school grade exhibited positive predictive value. Students in higher school grades were more likely to be in one of the more proficient *control proficiency* or *advanced proficiency* profiles. However, after inclusion of content knowledge, the parameter estimates for grade predicting profile frequencies were very close to zero. Thus, the predictive value of grade was again explained by students' content knowledge. The relationship between students' content knowledge and proficiency profiles is depicted in Figure 7.

With increasing content knowledge, students were generally less likely to show either of the less proficient *basic proficiency* and *moderate proficiency* profiles and more likely to show the more advanced *control proficiency* or *advanced proficiency* profiles. The two intermediate profiles, *average proficiency* and *planning proficiency*, showed a slight increase in frequency across the

lower range of content knowledge, but in the higher range of content knowledge the frequencies of these two profiles again decreased. Dotted lines in Figure 7 indicate students' median content knowledge in each school grade. Fifth graders, the youngest students in the sample, showed a median content knowledge of about 1SD below average. These students mostly showed the *basic proficiency*, *moderate proficiency*, or *average proficiency* patterns. Thus, fifth graders possess a varying, yet rather low, degree of proficiency on the CVS sub-skills. Around seventh to tenth grade, the frequency of students in the *control proficiency* profile starts to increase strongly, going hand in hand with an increase of content knowledge up to 0.5 SD above average. Only in eleventh grade and beyond, at a content knowledge level of about 1SD above average, does an increase in the *advanced proficiency* profile set in. This indicates that in the highest grades, about one quarter of students start grasping the difficult to understand sub-skill in addition to the other sub-skills. With content knowledge 2SD above average, about 70% of students are estimated to possess advanced proficiency of all four CVS sub-skills; however, this level of acquired content knowledge was only reached by a small number of 24 (1.9%) students of the whole sample.

Additional Analyses

The understanding items were more difficult than the other sub-skills, and the underlying skill developed much later than the other sub-skills. It is possible that this difference in difficulty emerged because the students may have misunderstood the items (i.e., understanding them as being about what they think influences the experimental outcome, rather than being about what the outcome shows). Therefore, we additionally analyze the distractors chosen by the students. On understanding and interpretation items (see Table 6), the answer options are identical; but, they have different meaning: Both items show the outcome of an experiment and ask students to interpret what can be concluded from the experiment. The only difference between the items is that

UN items show confounded experiments while IN items show the outcome of controlled experiments. Accordingly, the correct interpretation of UN items is that “the experiment does not allow any valid conclusion” and for IN items that the variable varying between the contrasted cases has an impact on the outcome. We analyzed the frequencies of students’ choices of the different answer options on both types of items, in order to check that their answers reflect a lack of the respective skill rather than a misunderstanding of the item. As Table 6 shows, option three and four were chosen more frequently for UN items (when cases that vary on two variables were presented). Based on these data it seems very unlikely that students chose these answers accidentally, or because they overlooked the confounding variable, or because they misunderstood the items as a question about what they think influences the experimental outcome. Rather, these answer patterns indicate that students indeed failed in solving the UN items because they believed that it is possible to test more than one variable in a contrast that varies on two variables (answer option three).

Discussion

This study aimed (1) to examine the development of CVS and (2) to estimate the relation between CVS and science content knowledge throughout secondary school. Analyzing data from a large sample of students from grades 5 to 13, we found that CVS proficiency increases with grade level; however, this increase can be explained by concomitant development in students’ science content knowledge. Our statistical analyses also indicate that the sub-skill of understanding the indeterminacy of confounded experiments (UN) is more difficult and that it emerges later than the three other sub-skills.

The Structure of the Sub-Skills Amounting to CVS

From the view of confirmatory factor analysis, CVS was modeled as a coherent skill with sufficient model fit. From the view of latent profile analysis, however, there was a mix of linear

and non-linear patterns in students' CVS skills. By combining both analytic techniques, we analyzed the structure of the CVS construct and changes in students' CVS skills over the course of secondary school. The latent profile analysis revealed a clear separation between students mastering and students not mastering the UN sub-skill. Achievement on this skill might therefore develop stagewise rather than in a continuous manner. In accordance with our prediction (hypothesis 2.2), the only profile in which students master the UN sub-skill is composed of those who also master all the other sub-skills.

The planning proficiency profile is composed of students who manage to set up a controlled experiment. However, these students do not draw the correct conclusions from controlled and confounded experiments. The prevalence of this profile was rather low, and it further decreased in higher grades. We assume that such a profile arises when students have a rather implicit understanding that a good experiment only varies a single variable of interest at a time. What these students lack is an explicit understanding of how this experimental design principle relates to the inferences that one can draw from an experiment. Future research should identify these students using a latent profile analysis, to interview them about their understanding of the relation between experimental design and inference. The frequency of this profile decreases in higher grades, which might indicate that students learn to connect their prior understanding of experimentation to valid and invalid inference when they engage in experimentation and inference in physics instruction.

There were clear differences in CVS skills over the course of secondary school. Nonetheless, grade level did not explain any additional variance in CVS skills beyond that explained by science content knowledge. This underlines students' science content knowledge as a central predictor for their overall CVS skills, and for their capability of the difficult UN sub-skill in particular. An explanation for this close relation between CVS and science content knowledge

is that proficiency in CVS helps students to build causal knowledge from their inquiry activities. This means both constructs are correlated because applying CVS supports learning of science content knowledge. However, as we just have correlative data the relation might be inverse - that content knowledge might help students to apply CVS or to identify confounded experiments. Of course, the relation could be more complex as both processes could happen simultaneously (Schauble, 1990, 1996). For the present data, the latter relation is most likely, such that an increase in science content knowledge leads to an increase in CVS skills within associated science-contexts. Most students in the included German schools undergo physics instruction in grades 6 and 7. The impact of the instruction is clearly visible cross-sectionally in an increase in students' science content knowledge. Within physics instruction in German schools, CVS is usually not a tool that is of central importance. Usually teachers guide students through experiments, and subsequently pose and discuss the question "What does the experiment show?" Therefore, it is likely that students' science content knowledge helped them solve the CVS items, rather than the other way around.

Additional analyses of the distractors chosen by students suggest that the tendency to infer causal relations from confounded experiment represents misconceptions about experimental design. The distractor stating that variable A and B both have a causal impact relates to the misconception that more than one variable can be investigated in an experiment with a single contrast (Siler & Klahr, 2012). The fact that students chose this answer option much more often than the two further distractors stating that a single one of the two confounded variables has a causal impact indicates that students answered UN items incorrectly because they did not realize the indeterminacy of confounded experiments. In general, students showed a high confidence in

experimental results; only few students stated that confounded experiments are invalid, and none doubted the evidence from controlled experiments.

Theoretical and Practical Implications

Our findings have implications for educational theories and science teaching. The results indicate that students' cognitive development does not result in an overarching general CVS skill, but rather are bound to very specific sub-skills. This offers one explanation for the large variance in individuals' CVS skills reported in many studies (for a review see Zimmerman, 2007). Differences in proficiency in the understanding (UN) and the remaining sub-skills might result from different experiences that are required for achieving these skills. While the planning, identification, and interpretation sub-skills develop when students reflect on evidence i.e. "which claims can I make from the evidence?", the more demanding understanding sub-skill requires reflection on the processes of evidence interpretation and generation itself i.e. "why can I (not) make certain claims from the evidence?". This means that the hierarchical structure of CVS sub-skills indicated by students' profiles across the sub-skills emerges because the other three aspects are a premise for achieving full reflective mastery CVS, which is required in the UN tasks. An explanation for this special role and demands of the UN sub-skill might be that this is a more metacognitive aspect of CVS (Zohar & Peled 2008). However, with direct instruction in the UN sub-skill, students might be able to master the understanding sub-skill before or at the same time as the remaining sub-skills. Such intervention studies are necessary to find out whether the identified structure represents a determined pathway of cognitive development, or just the regular experiences of secondary school children.

The association of science content knowledge and CVS skills suggests that the development of science concepts and scientific reasoning skills are related and maybe depend on each other.

This is one reason why learning and doing science is challenging, because it requires at least science content knowledge and scientific reasoning skills. Intervention studies that isolate the effect of CVS instruction on science content knowledge and vice versa are necessary for deeper understanding of these relations. Prior intervention studies examining students' belief change after CVS training and ensuing experimentation provide evidence for a positive effect of CVS interventions on students acquisition of science content knowledge (Chen & Klahr, 1999, Stender, et al. 2018), however an extended focus on this relationship would enable more detailed insights into the strength and processes behind this relation.

Enabling students to investigate and debate causal relations based on experimental data is a major aim of science education. To achieve this aim, students need to acquire at least three prerequisites: (1) cognitive aspects of CVS i.e. How to apply CVS?, (2) the meta-cognitive aspect of CVS i.e. Why to apply CVS and what happens if CVS is violated? and (3) science content knowledge. Our results suggest that omitting any of these three aspects can hinder efficient and valid causal reasoning. Without the cognitive aspects of CVS, students are unable to plan, interpret or identify meaningful experiments for investigating causal relations. An absence of the metacognitive understanding results in a production deficit, failing to apply available CVS skills in a manner that allows drawing valid inferences (Thillmann, Gößling, Marschner, Wirth, & Leutner, 2013). Finally, science content knowledge is crucial for identifying variables and interpreting experimental data. However, as our results show, only a few students in grades 11 to 13 understand why confounded experiments lead to inconclusive evidence. Consequently, we suggest that in science education, developing metacognitive CVS skills should be in focus early in secondary school. Although the present data are just correlative, they suggest that introducing

single CVS skills, particularly focusing on the understanding of confounding, might have positive effects on other aspects.

Advances of our Analytic Approach

We believe that the present analytic approach, using both confirmatory factor analysis and latent profile analysis, allowed insights into the structure of students' CVS skills that would not be possible with more traditional regression analyses, or with just either of the two present analyses. The confirmatory factor analysis showed that it is possible to estimate a latent variable representing a general CVS skill with adequate model fit. This might imply that students who are good at one sub-skill also tend to be good at the other sub-skills. This finding could indicate a common core of students' CVS skill, for example a kind of abstract understanding of the underlying principle which, to the level that it is acquired, transfers across situations of various kinds representing the different CVS sub-skills. However, such conclusions might be premature, which becomes evident by consulting the results from the latent profile analysis. Combining the results from our two types of analysis, it can be seen that the confirmatory factor analysis-approach overlooks substantive information in the data. This was indicated by non-linearity in the latent profile analysis; that is, some of the profiles that crossed each other. Such overlapping profiles represent subgroups of students for which a specific level in one sub-skill is not a valid predictor of level in the other sub-skills. As shown by Edelsbrunner and Dablander (2019), this non-linearity in the data is not visible in regular regression analysis or the commonly applied Rasch model (e.g. in Schwichow et al., 2016). Therefore, we suggest considering the application of latent profile analysis or similar statistical approaches in future studies investigating multiple CVS sub-skills.

Limitations and Outlook

We assessed only science content knowledge and CVS skills and did not consider other important facets of scientific reasoning, such as hypothesis generation skills and epistemic cognition (Mayer, et al., 2014). Different scientific reasoning skills can show substantially different patterns of correlations with external variables (Osterhaus et al., 2017). Therefore, the present results should not be interpreted as being representative of general scientific reasoning. In addition, the items were embedded in the context of two physics topics that students in Germany learn in high school. While this offered the advantage that it provided a cross-sectional view on the impact of the relevant physics instruction, we assume that in less strongly contextualized items (e.g., not requiring content knowledge for identifying relevant variables), the relationship between CVS and content knowledge would be less pronounced. Yet, the contextualization in the present study allowed examining the degree to which solving CVS items depends on relevant content knowledge that is acquired in science education. Furthermore, the present study is cross-sectional. This inhibits drawing strong conclusions, particularly about the strength of the impact of content knowledge on CVS and about the developmental nature of the CVS profiles. Based on these limitations and the questions that the present findings raise, we recommend several avenues for future research. In future studies, it would be highly interesting to implement a repeated measures design, assessing students at least twice, for example in consecutive school years. This would enable examining students' developmental patterns on the four CVS sub-skills over time, which could be elegantly modeled by means of latent transition analysis (Hickendorff et al., 2018). Based on the present findings, we would, for example assume that students develop from the planning proficiency profile to the control proficiency profile. In addition, assessing science content knowledge would allow examining whether science content knowledge can predict students' development on the different sub-skills, and vice versa. Another informative opportunity would arise from directly

training students on CVS and assessing the effect of the intervention across the four sub-skills. An intervention aimed at supporting students' development of the demanding UN sub-skill might show transfer to the other sub-skills. Although training this metacognitive understanding is difficult, prior evidence indicates that it is indeed possible (Zohar & Peled, 2008). Such training would allow us to examine whether a direct intervention can trigger students to develop profiles across the CVS sub-skills that differ from those in the present data. For example, it would show whether it is possible for students to possess understanding of the more reflective and metacognitive UN sub-skill but lack proficiency in the other more procedural and less reflective skills. Overall, both intervention studies and developmental studies offer informative avenues for future research that could provide insights into different facets of the development of CVS and its relation to science content knowledge.

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Susan thinks that the heating of a wire in a circuit depends on the wire material.

Her hypothesis is that iron wires getting hotter than copper wires.

Please design an experiment to test Susan's hypothesis by selecting wire materials and battery type for two contrasting cases.

case 1		case 2

☒ copper ☐ iron	wire material	☐ copper ☒ iron
☒ small ☐ large	battery	☐ small ☒ large
<input type="button" value="submit"/>		

Figure 1. Example of a planning (PL) item. All contrasts of cases that use the same battery but different wire materials are correct answers.

Clothes	ID-SO-1
<p>Anna wants to buy a new shirt. Because it is summer she wants to buy a shirt that keeps cool.</p> <p>She assumes that a white shirt would be better than a dark one because in the sun white shirts are not getting as warm as dark shirts.</p> <p>Which of the following experiments would be a good experiment to test her assumption?</p>	
☐
☐
☐
☐

Figure 2. Example of an identification (ID) item in the context of “heat and temperature” (option two is correct as it is a controlled experiment).

Bright light	UN-LS-2
Toni did the following experiment:	
<p>Room temperature 30°C</p>	<p>Room temperature 10°C</p>
What does his experiment show?	
☐	The material of the wire has an impact on the brightness of the bulb.
☐	The room temperature has an impact on the brightness of the bulb.
☐	The wire's material and the room temperature have an impact on the brightness of the bulb.
☐	The experiment does not allow any valid conclusion.

Figure 3. Example of an understanding (UN) item in the context of “electro/magnetism”. *Note.* Option four is correct as the figure displays as confounded experiment. Interpreting (IN) items are identical except they show controlled experiments so that option one or two is correct.

Figure 4. Distributions of z-standardized CVS sub-skills and science content knowledge (CK) across school grades. Solid black lines indicate means, color-shaded areas 95% highest density intervals, jittered points individual scores, and symmetrically outlined regions kernel density estimates.

Figure 5. The model predicting CVS indicated by students' achievement on the identification (*ID*), planning (*PL*), interpretation (*IN*), and understanding (*UN*) sub-skills from students' school grade and content knowledge (*CK*). Parcel of content knowledge items regarding heat and temperature (*HT*) and electro/magnetism (*EM*). Standardized parameter estimates. Regression path of CVS on CK $p < .001$, CVS on grade (in dashed grey) $p > .05$.

Figure 6. The six estimated student profiles across the four CVS sub-skills, including estimated profile frequencies in % and the profile labels elaborated in the text.

Figure 7. Relationship between students' content knowledge and estimated frequencies of CVS profiles. Points indicating profiles frequencies are slightly jittered for better readability. Grey dashed lines indicate the median content knowledge for different school grades.

Table 1. Distribution of students across school grades.

Grade	5	6	7	8	9	10	11	12	13
Mean age (SD)	10.45 (0.65)	11.40 (0.56)	12.36 (0.63)	13.40 (0.55)	14.44 (0.63)	15.51 (0.69)	16.78 (0.69)	17.19 (0.78)	18.50 (0.81)
Number of students	172	165	153	211	172	173	60	107	70

Table 2. Model fit statistics for measurement invariance of the Rasch-models for the four CVS sub-skills across school grades. Students were grouped into grades 5-7, 8-10, and 11-13 in order to yield sufficiently big samples for these analyses.

		Chi2	df	RMSEA	CFI
Identification	Configural invariance	167.52	142	.02	.98
	Weak invariance	227.51	144	.04	.95
	Strong invariance	189.13	162	.02	.98
Planning	Configural invariance	244.36	173	.03	.99
	Weak invariance	341.79	175	.05	.97
	Strong invariance	252.46	195	.03	.99
Interpretation	Configural invariance	220.45	173	.03	.96
	Weak invariance	227.25	175	.03	.96
	Strong invariance	267.13	195	.03	.94
Understanding	Configural invariance	225.05	142	.04	.99
	Weak invariance	322.30	144	.05	.98

Table 3. Results of on-way ANOVAS to check for systematic differences between schools.

Dependent Variable	F(2,1281)	p value
Planning (PL)	0.14	0.87
Identification (ID)	0.19	0.83
Interpretation (IN)	1.40	0.25
Understanding (UN)	2.63	0.07
Content Knowledge (CK)	1.09	0.34

Table 4. Internal consistency estimates (ω) and intercorrelations (Pearson r) of main study variables.

	ω	School grade	Content knowledge	Identificatio n	Plannin g	Interpretation
Content knowledge	.58	.56				
Identification	.83	.49	0.48			
Planning	.92	.53	0.49	0.67		
Interpretation	.78	.43	0.42	0.56	0.51	
Understanding	.89	.36	0.30	0.33	0.32	0.37

Table 5. Fit indices of the latent profile analyses with 1-8 profiles. AIC = Akaike information criterion, BIC = Bayesian information criterion, aBIC = sample-size adjusted Bayesian information criterion, LRT = Vuong-Lo-Mendell-Rubin likelihood ratio test ($p < .05$ indicates model fits better than with one class less), Entropy = classification reliability.

Profiles	AIC	BIC	aBIC	LRT (p)	Entropy
1	14349	14395	14366	NA	1
2	12964	13036	12992	< .001	0.87
3	12591	12689	12629	< .001	0.82
4	12457	12581	12504	.098	0.77
5	12297	12446	12354	< .001	0.86
6	12171	12347	12239	.006	0.88
7	12123	12324	12200	.199	0.88
8	12020	12247	12107	.086	0.89

Table 6. Answers of students to interpretation (IN) and understanding (UN) items by chosen answer options.

	Answer 1	Answer 2	Answer 3	Answer 4
	Variable X has an impact ...	Variable Y has an impact ...	Variable X and Y have an impact ...	... no valid conclusion
Interpretation (IN)	38.91%	49.03%	12.06%	00.00%
Understanding (UN)	17.44%	20.20%	35.60%	26.76%

Note. Options one to three end with "...on the outcome of the experiment" and option four was originally phrased as "The experiment does not allow any valid conclusion". For IN items answer one or two is correct and for UN items always answer four is correct.