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Short Review

How can scientific thinking be fostered in the classroom?

Inquiry-based fostering of scientific thinking[1] is a central task of STEM education in schools. Students do not develop this skill on their own, but only through targeted guidance and practice. One of the most important methods of scientific inquiry is the control-of-variables strategy (COV). Numerous studies have examined whether and how understanding of this strategy can be fostered in the classroom. The meta-analysis »Teaching the control-of-variables strategy: A meta-analysis« by Schwichow, Crocker, Zimmerman, Höffler, and Härtig (2016) analyzes the findings from 72 studies and compiles important insights into effective measures for promoting the control-of-variables strategy in the classroom.

INTRODUCTION. Scientific thinking is a core competency for STEM subjects and a central component of current educational standards. The ability to think scientifically helps students address and solve a wide range of problems in both scientific and everyday contexts. A fundamental goal of scientific thinking is to find valid explanations - for example, in the form of cause-and-effect relationships - for a variety of phenomena, as well as to be able to justify and substantiate them convincingly. To do this, suitable conditions must be identified or deliberately created that allow for the clearest possible conclusions about cause-effect relationships. This means that in an experiment or a series of experiments, all potential explanations are ruled out one after another as far as possible, until only demonstrably causal explanations for a phenomenon remain (see example). This experimental approach is known as the Variable Control Strategy (VCS).

META-ANALYSIS AT A GLANCE

Focus of the study	Effective promotion of the variable control strategy as a central component of scientific thinking
Target group	Primarily 10- to 15-year-old students
Average Effect Size	Moderate effect on the promotion of the variable control strategy ($g = 0.61$)
Additional Findings	The use of demonstrations (moderate effect: $g = 0.69$) and cognitive conflict (large effect: $g = 0.80$) is particularly effective

The Variable Control Strategy plays a central role in research and science and, considering the increased emphasis on scientific thinking and work in educational standards and curricula, is a key focus as a teaching objective. The goal is not only for students to be able to generate

[1] You can find definitions of the underlined technical terms in our online glossary with a single click.

causal evidence themselves through experiments, but also for them to understand underlying scientific strategies, learn to critically evaluate, and reason about proposed explanations in a scientific manner. The question of whether and how the variable control strategy can be effectively promoted has been the subject of numerous studies for decades. The present meta-analysis summarizes the current state of research and provides important insights into how instruction can be optimally designed in this context.

THE VARIABLE CONTROL STRATEGY: EXAMPLE

To determine the role that irrigation plays in plant growth, experiments are conducted in which identical conditions are created for two plants: The same plants, the same light, the same soil, the same fertilizer, etc. Only the amount of water added varies. This means that all possible and known variables except for the amount of water are controlled. If one plant grows more or less than the other, this can be clearly explained by the difference in water supply. This allows the hypothesis that irrigation has an influence on plant growth to be experimentally substantiated.

WHAT IS THIS STUDY ABOUT? An initial meta-analysis promoting the Variable Control Strategy was published as early as 1988 (Ross, 1988). Since then, a large number of new studies have been published, which Schwichow and colleagues can now draw upon. The number of available studies and the further-developed meta-analytic methods allow them to explore in detail under what conditions scientific thinking and the Variable Control Strategy can be particularly effectively promoted. To this end, they identify and examine a wide range of influencing factors, known as moderators: A first set of questions addresses certain characteristics of the students (e.g., age); a second set addresses instructional design features (see *Table 1*); and a third examines how the type of testing influences the results[2].

For their analyses, Schwichow and colleagues draw on a total of 226 effect sizes from 72 individual studies with experimental or quasi-experimental designs. They were published between 1972 and 2012. Eight of the studies were conducted in Germany; the rest were conducted primarily in the United States or other European, Asian, and American countries. In total, 5,355 students participated in the studies.

WHAT DID THIS STUDY FIND? Scientific thinking can be fostered through instruction: Schwichow and colleagues replicate Ross's (1988) findings and determine a mean effect size of g = 0.61 (medium effect). The moderator analyses of instructional design features yield several interesting insights (see also *Table 1*):

Instructional focus. The analysis shows that, in terms of learning success, it makes no decisive difference whether the instruction focuses exclusively on teaching the variable control strategy or whether the teacher simultaneously pursues other goals, such as imparting factual knowledge.

[2] The following section presents the key findings regarding the first and second research questions. Information on the third, more methodologically oriented question can be found in the evaluation of the meta-analysis (see "How does the Clearing House for Instruction evaluate this study?").

Method of instruction. There has been a long-standing debate on whether teaching an explicit mnemonic for the Variable Control Strategy leads (in the long term) to better learning outcomes than when students "discover" the VCS on their own through experimentation. Such a mnemonic might, for example, read: "Always vary only one variable at a time." No clear preference can be derived from the corresponding moderator analysis: Therefore, there are also effective ways to teach the Variable Control Strategy without formulating an explicit mnemonic.

Table 1. Instructional design features examined.

MODERATOR	SUPPORT STRATEGY	EFFECT-SIZE (*g*)
Instructional Focus	Mastering the variable control strategy is the sole instructional objective	0.63
	Additional instructional objectives beyond the variable control strategy (e.g., factual knowledge) are taken into account	0.58
Teaching Method	The lesson provides students with an explicit mnemonic for the variable control strategy, which can be used to solve typical problems	0.58
	The lesson does not include an explicit mnemonic	0.65
Opportunities for Practice	Instruction provides opportunity(ies) to conduct experiments—either in real life or via computer simulation—on their own	0.59
	Students have no opportunity to actively experiment on their own	0.74
Use of Feedback	Students receive feedback on the experiments they conduct (in writing or orally)	0.66
	No feedback	0.58
Use of demonstration(s)	Demonstration of an exemplary experiment (in real life or via computer simulation)	0.69
	No demonstration	0.48
Use of cognitive conflicts	Students are confronted with experiences that do not conform to their expectations; this is intended to generate cognitive conflicts	0.80
	No generation of cognitive conflicts	0.53
Instructional context	Classes held on school premises on topics such as spring tension or bacterial reproduction	0.56
	Classes held off-campus on topics such as bouncing balls or rocket design	0.72

Opportunities for practice. Current research suggests that opportunities for practice in which students can actively experiment on their own have positive effects on the acquisition of the variable-control strategy. The moderator analysis, however, shows that the availability of such

opportunities does not play a significant role. The authors explain this finding by noting that the variable control strategy is primarily a cognitive strategy: Engaging with the concrete execution of experiments - whether real or in computer simulations - may distract from the essential features of experimental design and the experimental strategy, or at least provide no added value. This could also explain why it does not matter whether students receive *feedback* (written or oral) on the *conduct* of their experiments[3].

Demonstrations. Demonstrations of correctly conducted experiments, on the other hand, offer the advantage that students - unlike when conducting experiments on their own, where they must attend to many technical and practical aspects - can focus entirely on understanding the central (design) features of the experiment and the experimental strategy. The facilitator analysis shows that this element does indeed make a decisive difference.

Cognitive conflict. Particularly when combined with demonstrations, the creation of cognitive conflicts has a positive effect on learning outcomes. A cognitive conflict occurs when the result of an experiment does not match the students' expectations. It can be generated, for example, by showing researchers who do not adhere to the variables of a control strategy and obtain ambiguous and/or unexpected results in their experiments. When implemented appropriately, cognitive conflicts can enhance the effectiveness of learning: The teacher must clarify the cognitive conflict by first asking the students about their expectations before the demonstration. If students are then guided to explore explanations for the unexpected result and their own - possibly erroneous - beliefs, a deeper understanding of the underlying relationships is enabled. (See also *Example Study* & *Conclusion for Classroom Practice*.)

Instructional context. One assumption that has not yet been explicitly tested is that students may be more enthusiastic about out-of-school *contexts* and, accordingly, learn the Variable Control Strategy better in such contexts. However, the analysis of the instructional context could not confirm this assumption: Students learn the Variable Control Strategy with similar success in both school and out-of-school contexts.

HOW DOES THE CLEARING HOUSE UNTERRICHT EVALUATE THIS STUDY? The *Clearing House Unterricht Research Group* evaluates the meta-analysis based on the following five questions, guided by the Abelson criteria (1995):

How substantial are the effects? According to the standard classification by Cohen (1988), the average effect size falls within the moderate range (g = 0.61). This effect appears to be highly stable with respect to variables that frequently influence the results in other meta-analyses (e.g., age or methodological factors) and was derived from valid primary study designs. In some cases, the students in the control groups were taught the same topic but without a focus on the Variable Control Strategy. This ensures extremely fair and rigorous comparison conditions. It also appears that by employing cognitive conflict, the effect can even be amplified to a large effect (g = 0.80). This large effect means that nearly 80% of the students

[3] Supplementary finding: In an experimental study, the authors investigated the effect of actively conducted experiments on learning the VCS compared to worksheets. The results show that actively conducted experiments have a positive effect on the conduct of real-world experiments, whereas worksheets have a positive effect on the evaluation of experiments presented in writing. This effect occurred only when the content of the practice and test materials was the same. In transfer tasks with different content, there was no difference between the students in the two groups (Schwichow et al., 2016).

in the experimental group demonstrate higher performance in scientific thinking than the average of the control group.

How differentiated are the results? The *Clearing House Research Group* assesses the differentiation of the reported effects based on school subjects, grade levels, and the success criteria. Specific school subjects were not examined in this meta-analysis, as scientific thinking is considered across subject boundaries. The results are reported separately for different age groups; however, no differences are evident here. As the criterion of success, only performance in scientific thinking with a focus on variable control was examined.

How generalizable are the findings? The meta-analysis examined numerous moderators; for many of them, no significant differences were found between the (instructional) variants studied. In this respect, the reported average effect of teaching the Variable-Control Strategy can be generalized for some moderators. These include the students' age, whether the study was conducted in a classroom setting (vs. in a laboratory), the type of publication, and a variety of testing parameters (e.g., number of manipulable variables, highlighting of the most influential variables, authors of the test, time interval between instruction and testing). It is also worth noting that it does not seem to matter whether the performance tests are conducted with content different from that covered in class. When students learn the Variable-Control Strategy in a specific classroom situation, they can also transfer their knowledge to comparable experiments with different content.

The test format - that is, the technical implementation of the test - proves to be a significant influencing factor. In this regard, the validity of the overall effect cannot be generalized without reservation.

What makes this meta-analysis scientifically relevant? This meta-analysis is considered highly significant for two reasons: First, it replicates and expands upon the current state of research and thus, contributes to updating the body of evidence. Second, by focusing on the Variable Control Strategy, it achieves an impressive level of specificity and concreteness. The way the detailed moderator analyses are conducted to elucidate the differences found in the reported effects is exemplary. Through the theoretically and empirically well-founded selection of moderators, the meta-analysis makes a substantial contribution to further developing the theory regarding the instruction of the Variable Control Strategy.

How methodologically reliable are the findings? The disclosure and justification of the methodological approach exemplarily meet the criteria of common guidelines (e.g., APA Meta-Analysis Reporting Standards). The steps involved in the search, selection, and analysis meet all requirements.

Further information on the assessment of the methodological approach can be found in our Rating Sheet.

CONCLUSION FOR CLASSROOM PRACTICE. The findings of Schwichow and colleagues are highly relevant to everyday classroom practice: In all of the in-depth findings, school-related content was taught, and all of the measures described for increasing instructional effectiveness can be implemented without significant effort. The meta-analysis also includes several studies with numerous effect sizes from Germany. Overall, the reported effects prove to be very stable. The meta-analysis's focus on the Variable Control Strategy allows for the identification of specific details. On this basis, concrete recommendations for possible decision-making options in the planning and design of instruction can be derived.

First and foremost, the meta-analysis shows that many parameters hypothetically thought to influence the teaching of the Variable-Control Strategy do not play as significant a role as assumed. The authors, however, identify two crucial levers for the effective teaching of scientific thinking:

• Demonstrations should definitely be part of standard instruction.

• Cognitive conflicts can significantly increase the effectiveness of instruction.

The authors see great potential particularly in the combination of these two measures - for example, by guiding students to engage with the experiments in the demonstration that were designed with errors. When students can focus on designing experiments and thus, on the experimental strategy without being distracted by the technical details of the procedure, this appears to be a key to effectively mastering the Variable Control Strategy - and thus, a core component of scientific thinking.

EXAMPLE STUDY

In their experimental field study, Strand-Cary and Klahr (2008) identified a particularly strong effect of demonstrations, combined with the cognitive conflicts they generate, on scientific thinking. The 72 students, aged nine to twelve, participated in the experiment in two different groups (experimental vs. control group), each using two wooden ramps and balls. Their task was to determine whether a specific characteristic of the ramp (variables: steepness, length, surface of the ramp) influenced how far the ball rolled - that is, whether there was a causal relationship.
In the control group, the students were able to conduct experiments with the ramps on their own. In the experimental group, the students were explicitly instructed to work with the Variable Control Strategy: They first conducted their own experiment, and then they were shown both an incorrect version of the experiment - in terms of the Variable-Control Strategy - and a correct version (demonstration), during which the students were asked to explain why their expectations were not met in the incorrect experiment (*cognitive conflict*). In the experimental group, significantly more students learned to master the Variable Control Strategy than in the control group (difference $d = 2.0$).

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LINKS.

To the meta-analysis by Schwichow et al., 2016

To the study example by Strand-Cary et al., 2008

Additional research findings, teaching materials, and assessment tools: Scientific-reasoning.com (Martin Schwichow's website)

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