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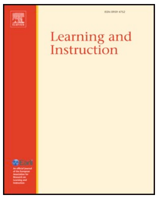

# Improved application of the control-of-variables strategy as a collateral benefit of inquiry-based physics education in elementary school

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ABSTRACT

In a quasi-experimental classroom study, we longitudinally investigated whether inquiry-based, content-focused physics instruction improves students' ability to apply the control-of-variables strategy, a domain-general experimentation skill. Twelve third grade elementary school classes ($Mdn_{age}$ = 9 years, $N$ = 189) were randomly assigned to receive either four different physics curriculum units (intervention) or traditional instruction (control). Experiments were frequent elements in the physics units; however, there was no explicit instruction of the control-of-variables strategy or other experimentation skills. As intended, students in the intervention classes strongly increased their conceptual physics knowledge. More importantly, students in the intervention classes also showed stronger gains in their ability to apply the control-of-variables strategy correctly in novel situations compared to students in the control classes. Thus, a high dose of experimentation had the collateral benefit of improving the transfer of the control-of-variables strategy. The study complements lab-based studies with convergent findings obtained in real classrooms.

## 1. Introduction

Gaining competence in science requires learners to develop domain-specific content knowledge, as well as domain-general experimentation skills, across educational levels (National Research Council, 2012; Sandoval, Sodian, Koerber, & Wong, 2014). Laboratory studies have indicated that these two competence components can bootstrap one another (Schauble, 1990, 1996). We investigated whether an aspect of this mutual benefit can be exploited in real classroom instruction. Specifically, we implemented four basic physics curriculum units in elementary school classrooms. These units were designed to support the acquisition of conceptual content knowledge through numerous experimentation activities in a guided inquiry approach. All experiments were designed to allow for valid inferences (i.e., they instantiated the control-of-variables strategy). Students were guided through the process of setting up experiments, making predictions, performing the experiment, observing and recording data, and drawing conclusions. However, the underlying strategies of valid experimental design, particularly the control-of-variables strategy, were not explicitly taught, and the learners were not confronted with any violations of this strategy. We longitudinally investigated whether content-focused instruction for elementary school students has collateral benefits (through its strong reliance on valid experiments) for the development of their ability to apply the control-of-variables strategy in novel contexts.

### 1.1. *Control-of-variables strategy and science education*

The control-of-variables strategy (CVS) is a central domain-general principle of scientific reasoning. It specifies that causal data inferences obtained in an experiment can only be drawn if only one variable has been manipulated at a time (Strand-Cary & Klahr, 2008; Tschirgi, 1980). Understanding the CVS is necessary to generate and test causal hypotheses; that is, to design conclusive and valid experiments and to critically evaluate the outcomes of experiments (D. Mayer, Sodian, Koerber, & Schwippert, 2014; National Research Council, 2012; Zimmerman, 2007). A first grasp of the CVS gradually emerges during childhood as a consequence of cognitive development and learning opportunities provided in school (Osterhaus, Koerber, & Sodian, 2017; Sandoval et al., 2014). Some kindergartners (van der Graaf, Segers, & Verhoeven, 2018) and first-graders (Sodian, Zaitchik, & Carey, 1991) can already recognize confounded hypothesis testing as being inappropriate. In elementary school, the ability to think scientifically, which includes the understanding of the CVS, constantly increases (Koerber, Mayer, Osterhaus, Schwippert, & Sodian, 2015). Nevertheless, many secondary school students (and even adults) struggle when asked to evaluate and design conclusive experiments (Bullock,

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Sodian, & Koerber, 2009; Zimmerman, 2007). This issue is concerning because understanding the CVS is an important predictor of competence development in science (Bryant, Nunes, Hillier, Gilroy, & Barros, 2015).

Deliberate training can benefit students' understanding of the CVS. According to a recent meta-analysis (Schwichow, Croker, Zimmerman, Höffler, & Härtig, 2016), this training has typically been short-term interventions that focused on teaching the CVS or on teaching the CVS and additional content. Such explicit training is most effective if it includes demonstrations of valid and invalid (confounded) experiments and induces cognitive conflict (e.g., by challenging student conceptions with anomalous outcomes of a confounded experiment). Explicit training can also enable students to apply the CSV to new problems and in novel contexts (Chen & Klahr, 1999, 2008; Lorch Jr. et al., 2010; Lorch Jr. et al., 2014; Strand-Cary & Klahr, 2008). Importantly, by describing a training as "explicit", we do not maintain that it involves direct instruction of or lecturing about the CVS (e.g., a teacher explaining the logic of the CVS standing in front of the class). Rather, we use the term to distinguish previous trainings of the CVS in which the CVS was the focus of instruction (e.g., by explicitly contrasting valid and invalid experiments or by providing explanations about the CVS in demonstration experiments) from our "implicit" training in the present study. That is, we investigated whether a student's ability to apply the CVS can implicitly benefit from a guided inquiry instruction designed to develop physics content knowledge.

### 1.2. *Guided inquiry and abstraction of the CVS through structural alignment*

With guided inquiry, we refer to instructional techniques that combine discovery learning with strong scaffolding from the teacher and the learning materials (Hmelo-Silver, Golan Duncan, & Chinn, 2007; R. E.; Mayer, 2004). Guided inquiry is an effective instructional approach in education (Lazonder & Harmsen, 2016). Researchers have provided evidence for its benefits in domain-specific conceptual knowledge development in science education throughout preschool (Leuchter, Saalbach, & Hardy, 2014), elementary school (Hardy, Jonen, Möller, & Stern, 2006), and secondary school (Hanauer et al., 2006; Linn et al., 2014).

In guided inquiry-based instruction, students engage in active and self-directed exploration of complex phenomena and situations. For example, they create, test, and evaluate their own hypotheses in experimentation activities. However, this process is not discovery learning. Instead, the teacher and the instructional material provide guidance to direct the student's attention toward the learning goals. For example, the materials prompt students to write down the expectations, observations, and outcomes of the experiments. Teachers pre-plan and structure the experiments, provide hints if students struggle, and secure understanding by synthesizing and discussing the students' findings after the experimentation activities. This type of guidance is beneficial for acquiring conceptual content knowledge (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011).

Inquiry serves not only as a method of supporting understanding of domain-specific contents but also developing inquiry skills is itself an important instructional outcome (Abd-El-Khalick et al., 2004). In accordance with this conceptual duality of inquiry, guided inquiry may have collateral benefits beyond supporting content knowledge acquisition. Indeed, Schauble (1990, 1996) has demonstrated a mutual relation between the development of domain-specific scientific content knowledge and domain-general experimentation skills in small-scale lab-based experiments. Corroborated by intensive case studies, Schauble showed that scientific content knowledge benefitted the development of learners' understanding of experimental strategies, such as the CVS and their ability to apply these strategies, and that, in turn, strategies improved content knowledge development. Recently, Edelsbrunner, Schalk, Schumacher, and Stern (2018) have provided additional empirical support for one direction of this mutual relation. In their large-scale study on guided inquiry-based instruction, elementary school students' understanding of the CVS positively predicted conceptual change in the domain of floating and sinking. Specifically, a better understanding of the CVS increased the probability that students gained scientifically correct conceptual knowledge and decreased the prevalence of misconceptions. However, the other direction of the mutual relation (i.e., how content-focused guided inquiry instruction may benefit the application of the CVS) is less well understood.

We suggest that research on learning by structural alignment and analogical reasoning (e.g., Alfieri, Nokes-Malach, & Schunn, 2013; Gentner, 2010; Richland & Simms, 2015) might provide an explanation for how the ability to apply the CVS might benefit from content-focused guided inquiry instruction. When humans compare two or more situations or instances, the result can be abstraction. That is, learners create a knowledge representation that contains only the structural similarities between the two situations. This abstraction sets the stage for flexible application in novel problems or contexts. In this sense, abstraction provides the basis for knowledge transfer (Chi & VanLehn, 2012; Gentner & Hoyos, 2017; Nokes-Malach & Mestre, 2013). Imagine a student who conducts several valid experiments (i.e., the experiments manipulate only one factor at a time) in various domains. Put differently, the student interacts with several instances of the CVS. If the student aligns these instances, this might support abstraction of the CVS because the CVS is a common structural feature across the valid experiments. Such spontaneous abstraction is rare in experimental laboratory settings with (rather) short interventions and a small number of examples; learners typically need specific scaffolds to abstract knowledge from few examples and to apply this knowledge in novel contexts (for overviews, see Gentner & Hoyos, 2017; Goldwater & Schalk, 2016). However, there is also evidence that analogical reasoning and abstraction are more frequent in naturalistic settings (e.g., Chan & Schunn, 2015; Dunbar, 2001) and when students encounter various examples over longer time periods, as in the studies by Schauble (1990, 1996). The reasons for these conflicting findings gained from laboratory studies and studies in naturalistic settings are not entirely clear. One plausible explanation is that naturalistic settings typically provide more opportunities and learning resources compared to the resources provided in laboratory studies (Hofer, Schumacher, Rubin, & Stern, 2018). Therefore, we assumed that if students conduct many experiments over extended time in guided inquiry-based instruction, this experience might support them in structurally aligning the experiments, hence, in abstracting the CVS as a domain-general principle. If students abstract the CVS, it would improve their ability to apply it in novel contexts, that is, to transfer their knowledge.

### 1.3. *The present study*

We aimed to scale up one aspect of Schauble's findings (1990, 1996) to real classrooms. Specifically, we investigated whether the ability to apply the CVS increases as a collateral benefit of inquiry-based physics education in elementary school.

Beginning in 3rd grade, we implemented guided inquiry-based curriculum units to convey basic conceptual physics content knowledge. Crucially, understanding of the CVS increases at this age (Bullock & Ziegler, 1999). Thus, we could test whether and to what extent this development additionally benefits from the content-focused curriculum units. The units encompassed the broad topics *Floating & Sinking*, *Air & Atmospheric Pressure*, *Sound & Spreading of Sound*, and *Stability of Bridges*. Within each unit, students engaged in multiple guided experimentation activities designed to highlight to-be-learned physics concepts. All of these experiments were conclusive; they exemplified the CVS (see Appendix A for additional information on the curriculum and for examples of these activities). Thus, students enacted the CVS in their guided inquiry activities. However, they were never informed of this strategy. Thus, in contrast to studies that explicitly trained the CVS