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Teaching the control-of-variables strategy: A meta-analysis

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ABSTRACT

A core component of scientific inquiry is the ability to evaluate evidence generated from controlled experiments and then to relate that evidence to a hypothesis or theory. The control-of-variables strategy (CVS) is foundational for school science and scientific literacy, but it does not routinely develop without practice or instruction. This meta-analysis summarizes the findings from 72 intervention studies at least partly designed to increase students' CVS skills. By using the method of robust meta-regression for dealing with multiple effect sizes from single studies, and by excluding outliers, we estimated a mean effect size of $g = 0.61$ (95% CI = 0.53–0.69). Our moderator analyses focused on design features, student characteristics, instruction characteristics, and assessment features. Only two instruction characteristics – the use of cognitive conflict and the use of demonstrations – were significantly related to student achievement. Furthermore, the format of the assessment instrument was identified as a major source of variability between study outcomes. Implications for teaching and learning science process skills and future research are discussed.

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In science, controlled experiments are crucial for drawing valid inferences about causal hypotheses. Valid inferences are only possible if an experiment is designed in a way that alternative causal effects or interactions can be excluded. Therefore, all variables except the one being investigated should ideally be held constant (or "controlled") across experimental conditions (Dewey, 2002; Popper, 1966). The cognitive and procedural skills associated with being able to select or conduct controlled experiments have been of interest to both science educators and psychologists who are interested in the development of scientific thinking. Descriptions of the specific skill of controlling experiments include "isolation of variables" (Inhelder & Piaget, 1958), "vary one thing at a time" (VOTAT; Tschirgi, 1980), and the "control of variables strategy" (Chen & Klahr, 1999). For the remainder of this paper, we will refer to this critical science process skill as the control-of-variables strategy (CVS).

Resulting from its fundamental importance in science, CVS is also addressed in standards and curriculum materials for science education. In particular, the *Framework for K-12 Science Education* (National Research Council, 2012) makes a distinction between the concepts and processes of science, outlining various scientific and engineering practices related to CVS such as asking questions, conducting investigations, and interpreting and using evidence. The *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013) are defined in the context of science and engineering practice. Furthermore, scientific process skills such as CVS are required for learning through inquiry as they enable students to conduct their own informative investigations. Reasoning on the basis of unconfounded evidence is crucial not only in science but in all argumentation about causality. Again, current science standards focus on skills such as the ability to construct arguments and to argue on the basis of evidence (NGSS, 2013; NRC, 2012), which require students to produce interpretable evidence. Hence, an understanding of the importance and principles of unconfounded evidence is required for critical thinking in general and is linked to broader educational goals, such as inquiry skills and argumentation (Kuhn, 2005a). The control of variables strategy, therefore, plays a supporting role in many of the science and engineering practices that are the focus of current science education reform.

The prominent role of CVS in scientific reasoning and science education has made it the focus of much research. The domain-general adaptability of CVS has also made it an ideal task for developmental psychologists to study cognitive development in children. For example, Inhelder and Piaget's (1958) theory that children's thinking develops from concrete to abstract was based, in part, on observations of children's performance on tasks that involve manipulating and isolating variables (e.g., pendulum task, ramps task). Consequently, investigations of people's ability to design and interpret controlled experiments can be classified as either *investigative studies*, in which the development of skill on CVS tasks is correlated with other measured skills or individual differences (e.g., Cloutier & Goldschmid, 1976; Linn, Clement, & Pulos, 1983), or *intervention studies*, which explore the impact of instruction on students' achievement on CVS tasks (e.g., Chen & Klahr, 1999; Lawson & Wollman, 1976).

Investigative studies show that even elementary students are able to *select* controlled experiments and to interpret unconfounded evidence when the experimental data are consistent with students' beliefs and preconceptions (e.g., Croker & Buchanan, 2011; Schulz & Gopnik, 2004; Sodian, Zaitchik, & Carey, 1991). However, it is also evident that students (Bullock & Ziegler, 1999; Croker & Buchanan, 2011; Kuhn, Garcia-Mila, Zohar, & Anderson, 1995; Schauble, 1996; Tschirgi, 1980) and even adults (Kuhn, 2007) perform poorly on tasks when the task domain includes information that conflicts with their current beliefs and preconceptions. Across many studies, it is evident that most students and even some adults do not have a generalized understanding of CVS because their ability to identify, select, or design controlled experiments depends on the task content or situational factors (Koslowski, 1996; Linn et al., 1983; for a review see Zimmerman & Croker, 2013). Additionally, Siler and Klahr (2012) outline the procedural misconceptions about controlling variables that have been identified. For example, students often over-extend a "fairness schema" to produce experiments that are completely equivalent (i.e., identical), they often have trouble making the distinction between a variable and the variable levels, and they often misunderstand the goal of the task as to be one that is consistent with engineering an outcome rather than finding out about the causal status of a single variable.

Decades of research on the development of scientific thinking in general, and on experimentation skills in particular, show a long trajectory that requires educational scaffolding (Klahr, Zimmerman, & Jirout, 2011; Kuhn, Iordanou, Pease, & Wirkala, 2008; see also Sodian & Bullock, 2008 for a collection

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