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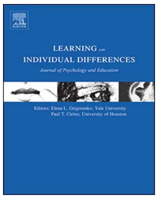

Variable control and conceptual change: A large-scale quantitative study in elementary school

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ABSTRACT

We examined the predictive value and interplay of elementary school students' understanding of the control-of-variables strategy, a domain-general experimentation skill, and their prior content knowledge for subsequent conceptual knowledge acquisition and conceptual change. Trained teachers provided $N = 1809$ first to sixth graders with 15 lessons of guided inquiry-based instruction on floating and sinking. We assessed understanding of the control-of-variables strategy before instruction, and conceptual content knowledge from before to after instruction. A mixture model analysis, specifically, a latent transition analysis, indicates that understanding of the control-of-variables strategy predicts content knowledge structure before instruction, and content knowledge development from before to after instruction. These findings corroborate lab-based research on the interplay of experimentation skills and content knowledge in inquiry settings and extend it to teacher-guided classroom instruction. We describe how learning pathways vary depending on students' understanding of the control-of-variables strategy and prior content knowledge, and discuss implications for learning and instruction.

1. Introduction

Conceptual change research has yielded many insights into students' development of conceptual knowledge. These insights have stimulated the generation of elaborate science units for kindergarten (Leuchter, Saalbach, & Hardy, 2014), elementary (Hardy, Jonen, Moeller, & Stern, 2006), and early secondary school (Smith, 2007). Often, science education in these first stages of schooling is based on inquiry. In general, inquiry-based science instruction, particularly under teacher-guidance, is an effective instructional means for developing conceptual content knowledge (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Furtak, Seidel, Iverson, & Briggs, 2012; Hattie, 2009; Slavin, Lake, Hanley, & Thurston, 2014). But not all students advance to the same degree. According to conceptual change theory, differences in the prior content knowledge that students bring to class can explain this interindividual variation. Students' knowledge representations differ because they have different experiences from everyday life and prior education (Carey, 1985, 2000).

Differences exist not only in content knowledge but also in students' understanding of experimentation. In inquiry-based instruction, students often engage in experimentation. Setting up and interpreting experiments requires adequate understanding of domain-general experimentation principles such as the control-of-variables strategy (CVS) (Kuhn, Black, Keselman, & Kaplan, 2000; Kuhn, Ramsey, & Arvidsson, 2015). There are other, more and less advanced steps in the development of knowledge about experimentation, however understanding of the CVS is pivotal (Croker & Buchanan, 2011; Kuhn, Iordanou, Pease, & Wirkala, 2008; Osterhaus, Körber, & Sodian, 2016; Piekny & Maehler, 2013; Sodian, Zaitchik, & Carey, 1991). Interindividual differences in understanding this domain-general strategy can be expected to influence the acquisition of scientific concepts. In the present study, we aim at scrutinizing the predictive value and interplay of students' understanding of the CVS and their prior content knowledge for subsequent knowledge acquisition and conceptual change in inquiry-based science instruction. Building on prior lab-based research, we examine this interplay in the context of real science classrooms, with a large-scale sample of elementary school students being instructed by their classroom teachers. For data analysis, we apply an innovative kind of statistical modeling, specifically, a latent transition analysis.

1.1. Conceptual change in science

When students enter science classrooms, they bring prior conceptions about the instructed topics derived from their everyday experiences (Carey, 1985, 2009; Hardy et al., 2006). Imagine children hanging out at a river. Sitting at the riverbank, they note that stones lie

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on the river ground but wood floats by; later they throw small wooden branches and flip yet another stone and see that the light pieces of wood float, while the stones sink to the ground. Watching a steamboat entering the port, they admire the captain whom they recognize to be essential for safe ship passage. An anchor is released and sits so firmly on the ground that it prevents any absconding of the massive iron object that floats on the water. Talking about their experiences, they come up with some explanations for their perceptions. They discuss that light things float, heavy things sink, and a captain keeps a ship floating.

The usefulness of conceptions arising from such everyday experiences is often limited for explaining scientific phenomena. The captain is not the decisive characteristic for a ship's floating ability and not all wooden things float. But these conceptions are not generally useless. They serve sufficiently well for explaining some occurrences of floating ability. However, these conceptions reach their limits when more and more phenomena are experienced. The conceptions are wrong from a scientific point of view, because they cannot explain all occurrences of floating ability, and therefore they are called misconceptions (Chi & Ohlsson, 2005). An important aim of science education is to help students to develop an understanding of scientific concepts. For phenomena of floating and sinking, these are the concepts of object density and buoyancy force. The step from misconceptions to scientific concepts is far. Intermediate conceptions can bridge the gap (Carey, 1992; Hardy et al., 2006). These conceptions typically develop when students blend information given in instruction and their prior conceptions (Hardy et al., 2006).

Intermediate conceptions are also sometimes deliberately introduced by teachers in order to simplify content, but still to prepare their students' future science learning. For example, when children think about floating and sinking, they often give explanations such as “light things float, heavy ones sink” or “small objects float, large ones sink”. They do not yet understand that weight and size interact as density and thus see these conceptions as independent of each other (Maclin, Grosslight, & Davis, 1997; Smith, Carey, & Wiser, 1985). A more elaborate but still limited intermediate conception would be “things made of wood float, while stones sink”. This material-based conception can explain more floating ability phenomena than the conceptions of weight and size, but it is still limited in its explanatory power. When learning science, students show diverse developmental patterns in how they change from misconceptions via intermediate conceptions to scientific concepts. To support this development, it is necessary to understand how these learning patterns are structured and constrained, and how optimal knowledge development can be supported.

1.2. Conceptual change in the science classroom

Powerful processes of knowledge restructuring have to be triggered to enrich students' initial stock of misconceptions with scientific concepts or first with intermediate conceptions. These processes are referred to as conceptual change (Chi, 2008; Chi & Ohlsson, 2005; Ohlsson, 2009). For example, novices often have difficulties in recognizing deep and meaningful relations between prior knowledge and newly acquired knowledge (diSessa, 2008). In such cases, newly acquired knowledge is not connected with prior knowledge, leading to fragmented knowledge elements that are stored independently of each other. Knowledge fragmentation decreases when students gain sufficient conceptual understanding of a domain to integrate knowledge pieces into more coherent and general knowledge structures (Linn, Eylon, & Davis, 2004). This and similar processes of conceptual change allow integrated knowledge structures to be built up, for example by learning that different phenomena can be explained by a single principle, concept, or theory (Ohlsson, 2009).

One effective educational intervention for promoting conceptual change in science is inquiry-based learning, in which students engage in the thinking processes and activities of scientists (American Association for the Advancement of Science, 1993). This often includes social, procedural, and epistemic activities such as arguing scientific ideas, engaging in experimentation, and interpreting evidence (Furtak et al., 2012). Inquiry-based learning is a successful method for teaching science across various topics and educational levels (Anderson, 2002; Bennett, Lubben, & Hogarth, 2007; Flick, 1995; Furtak et al., 2012; Minner, Levy, & Century, 2010; Shymansky, Hedges, & Woodworth, 1990). Particularly in combination with strong teacher guidance, students' learning benefits in comparison to other traditional instructional methods, such as direct instruction (Furtak et al., 2012). However, learning differs not only between traditional and inquiry-based instructional conditions. Also within similar inquiry-based instructional settings (e.g., within one classroom), students learn to different degrees. These different learning gains on the one hand reflect differences in students' prior content knowledge, but it has also been pointed out that specific domain-general experimentation skills influence students' knowledge development (Bryant, Nunes, Hillier, Gilroy, & Barros, 2015; Chen & Klahr, 1999).

1.3. Experimentation and learning from inquiry

A precondition for beneficial engagement in inquiry is a thorough understanding of experimental designs (Kuhn, 2002; Kuhn et al., 2000). A crucial facet of experimentation concerns varying the focal variable while keeping all other factors constant. This strategy is referred to as the control-of-variables strategy (CVS), or as vary-one-thing-at-a-time (VOTAT). Following this strategy allows making unambiguous causal inferences (Strand-Cary & Klahr, 2008). CVS predicts academic performance and science learning above and beyond general reasoning abilities (Bryant et al., 2015; Wüstenberg, Greiff, & Funke, 2012). Most but not all children typically develop some understanding of the CVS at ages 6–10, depending on task context and the number of variables that have to be controlled (Sodian & Bullock, 2008; Zimmerman, 2007). Development of the understanding of the correct variation of the focal variable initiates in early childhood (Piekny & Maehler, 2013; Sodian et al., 1991). Then, around age 10, development of broader understanding of the CVS emerges in many children (Penner & Klahr, 1996). The understanding of the CVS and its development are moderately related to children's verbal reasoning and vocabulary, and to their general science content knowledge (Wagensveld, Segers, Kleemans, & Verhoeven, 2015). However, thoroughly understanding and being able to apply the CVS is challenging, and even some undergraduates lack these competencies (Lin & Lehman, 1999).

The development of conceptions about scientific phenomena and understanding of experimentation are probably not independent from each other, but exhibit mutual influence. In observational lab studies, Schauble (1990, 1996) found evidence for this interplay when she studied belief revision about causal mechanisms in observational lab studies. Students' knowledge about causal relations influenced experimentation strategies, while students' experimentation strategies in turn influenced the acquisition of content knowledge about causal relations. Based on these studies, it has been widely acknowledged that experimentation skills and content knowledge interplay in inquiry settings (Zimmerman, 2007). Taking these lab-based findings as a starting point, we aimed to scrutinize the generality and potential of this interrelation in classroom education.

We do not know from prior research whether students' understanding of experimentation influences their development of domain-specific conceptual knowledge in a teacher-guided inquiry-based curriculum unit. Does teacher guidance level out or enlarge the impact of students' understanding of experimentation on further learning? There are arguments for both sides. When teachers guide students in setting up experiments and engage them in argumentation about the outcomes, this might sufficiently support inferences and knowledge development even for students who entered the curriculum with poor understanding of experimentation. Put differently, teachers might take the