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Abstract

Science education aims at developing students' knowledge of scientific concepts and principles. However, students differ in their prior knowledge and cognitive skills and thus follow different learning pathways. We examined whether and how experimentation skills predict elementary students' pathways of conceptual knowledge development in science education. First to sixth grade students (N = 1275) received 15 units of inquiry-based classroom instruction on the topic "floating and sinking". Students' experimentation skills were assessed before instruction. Their conceptual knowledge about floating and sinking was assessed before and after instruction. Latent profile transition analysis, a markov chain mixture model for continuous longitudinal data, revealed that students with higher experimentation skills were more likely to develop proficient and consistent knowledge of floating and sinking. We discuss theoretical implications of this finding, advantages of mixture models to examine conceptual knowledge development, and implications for science education in elementary school.

Keywords: science education; experimentation skills; knowledge structure; knowledge development; elementary school;

Introduction

In the past years, insights from research on conceptual change were applied to the development of science curricula for elementary school and early secondary school (Hardy, Jonen, Möller, & Stern, 2006; Smith, 2007). That early, students do usually not receive elaborate science instruction in their regular school curricula. However, Hardy and colleagues (2006) and Smith (2007) showed that early science instruction can provoke long-lasting knowledge development. These substantial and sustainable learning gains indicate the significant potential of early science instruction. Nevertheless, students benefit from science instruction to different extent (e.g., Schneider & Hardy, 2013).

In the present study, we examine which students benefit more or less from early science education. We investigate a potential source of inter-individual differences in knowledge development. In particular, we investigate whether and how elementary school students' experimentation skills predict conceptual knowledge development in an inquiry-based science curriculum.

Knowledge Development in Science Learning

When students enter science classrooms, they often bring strong prior conceptions about the instructed topics derived from their everyday experience. When these conceptions are wrong from a scientific point of view, they are referred to as misconceptions (Chi & Ohlsson, 2005). In the course of science education, such misconceptions should be replaced by scientifically correct concepts.

To replace misconceptions with scientific concepts, processes of conceptual change have to take place. Conceptual change encompasses powerful processes of knowledge restructuring that are in general difficult to achieve (Hardy et al., 2006). One such process is knowledge integration, in which newly gained knowledge is added to the present knowledge in a logically coherent manner (Linn, 1995). This process thus allows 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).

Novices often have difficulties in recognizing meaningful relations between prior knowledge and newly acquired knowledge on a deep level (diSessa, 2008). In such cases, newly acquired knowledge is not integrated with prior knowledge. This lack of integration leads to fragmented knowledge elements that are stored independently from each other. Knowledge fragmentation decreases when students gain sufficient conceptual understanding of a domain to integrate knowledge pieces into coherent, more general knowledge structures (Vosniadou & Brewer, 1992).

In some domains, students' knowledge development does not directly lead from misconceptions to scientifically correct concepts. Rather, there can be partially correct intermediate conceptions. For example, children might assume that wooden things float and iron things sink, based on the conception that material kind determines the floating of objects in fluids. This assumption can explain that heavy wooden bricks float in water and that small stones sink but it cannot explain why iron ships float and why some sorts of wood sink. Hence, such conceptions are sufficient to coherently explain many observations from everyday life but they would fail thorough scientific validation. Therefore, they are referred to as everyday conceptions (Carey, 1992). Altogether, conceptual change is a complex, multi-faceted process that should be assessed in detail to obtain fundamental understanding of students' conceptual knowledge development pathways in science learning.

Modeling Conceptual Knowledge Development

Conceptual change research typically relies on assessing qualitative data to capture the complex process of knowledge development in science (e.g., Vosniadou & Brewer, 1992). Schneider and Hardy (2013) suggested complementing this approach with quantitative statistical modeling techniques to describe trajectories of knowledge development. They employed latent transition analysis, a type of longitudinal mixture model, to depict third graders' learning in an inquiry-based curriculum on the topic "floating and sinking". Based on extensive questionnaire data, they evaluated students' misconceptions, everyday conceptions, and scientific concepts about the floating ability of objects in water.

By employing latent transition analysis, Schneider and Hardy (2013) could identify five knowledge profiles among the students. The five profiles represented groups of students that differed in their numbers of the three types of conceptions. For example, students in one profile showed a high number of misconceptions but low numbers of everyday conceptions and scientific concepts, indicating a rather low proficiency level. Another profile revealed a group of students with high numbers of all three kinds of conceptions, indicating a fragmented knowledge structure. In addition, Schneider and Hardy (2013) depicted the transitional pathways that students took in the course of the instruction. They found a small number of transitions to suffice for describing how students switched between the knowledge profiles in the course of instruction.

These results emphasize the importance of investigating interindividual differences in students' conceptual knowledge. The limited number of profiles and transitional pathways indicates that knowledge development follows idiosyncratic yet systematic patterns. However, it is still unclear which cognitive characteristics or skills predict students' knowledge development. Why do some students show less fragmented knowledge than others, and why do some students in the course of instruction develop more consistent and proficient knowledge structures than others?

Experimentation Skills

A cognitive skill that might contribute to knowledge development in inquiry-based instruction is the methodological understanding of experimentation. A crucial facet of experimentation concerns varying the focal variable while keeping all other factors constant. Following this strategy unambiguous causal inferences can be made (Strand-Cary & Klahr, 2008). Understanding and applying this strategy is referred to as the control of variables strategy, or simply as variable control. Various research has shown that most but not all children typically develop these skills at ages 6-10, depending on task context and number of variables, and that these skills can be trained successfully in teacher-guided interventions (Strand-Cary & Klahr, 2008; Chen & Klahr, 1999; Sodian, Zaitchik, & Carey, 1991). In observational studies, Schauble (1990, 1996) described how experimentation skills support belief revision about causal mechanisms. Less is known about the relation of experimentation skills to more complex concept learning.

The Current Study

Scientific reasoning, including experimentation skills, is assumed to be applied in the service of conceptual change or scientific understanding (Zimmerman, 2007). Therefore, experimentation skills might be related to students' concept learning from inquiry-based instruction. To the best of our knowledge, this assumption has not yet been tested on a quantitative basis. In the current study, we examine the relation between students' experimentation skills and knowledge development about floating and sinking in inquiry-based instruction. We hypothesize that experimentation skills are positively related to the consistency and proficiency of students' knowledge profiles. Furthermore, we expect that experimentation skills support learning trajectories into consistent and proficient knowledge profiles from before to after instruction.

To investigate these hypotheses, we use latent transition analysis as it explicitly acknowledges three crucial assumptions about science learning. First, it acknowledges differences in children's knowledge. Not all students enter classrooms with the same prior knowledge, and not all students end up with the same knowledge after instruction. In latent transition analysis, students are grouped into a finite number of profiles according to differences and similarities in their knowledge. In the present study, as in the study of Schneider and Hardy (2013), knowledge profiles represent groups of students that differ in their numbers of misconceptions, everyday conceptions, and scientific concepts about floating and sinking.

Second, latent transition analysis acknowledges that not all students learn to the same extent. Some students might thoroughly integrate their prior knowledge with newly acquired knowledge in the course of instruction. Other students might not be able to achieve a proficient state of knowledge and stay at their initial knowledge level. In latent transition analysis, this aspect is represented by estimates of the probabilities that students stay in their initial knowledge profile or change into other knowledge profiles from before to after instruction.

Third, to investigate sources of differences in students' knowledge development, covariates can be added to the latent transition analysis. In the present study, we use this possibility to examine how students' experimentation skills relate to profile frequencies before instruction and to transition probabilities between profiles from before to after instruction. We hypothesize that students with higher experimentation skills show increased probabilities to change into proficient and consistent knowledge profiles from before to after instruction, indicating knowledge restructuring and successful inquiry-based learning.

Method

Participants

We analyzed the data of 1275 first to sixth graders (*M*[age] = 8.56 years, *SD* = 1.30, *range* = 6 – 13 years) from elementary schools in the German-speaking part of Switzerland. The study was embedded within the Swiss MINT Study, a longitudinal study investigating outcomes of cognitively activating science instruction that starts in elementary school.

Learning Materials

Students learned about the physics topic "floating and sinking of objects in water", encompassing the scientific concepts of object density and buoyancy force. The instructional materials were developed and extensively tested at University of Munster, Germany (for details on the materials see Hardy et al., 2006). The materials comprised 15 lessons of teacher-guided, inquiry-based classroom instruction that can be adaptively used in first to sixth grade classrooms. Typically, children received either one lesson per week, or all lessons within a week. In grades 1-2, some basic lessons were emphasized while some more advanced lessons were omitted. The materials strongly scaffold inquiry-based learning activities (e.g., structured hands-on experiments) and include established instructional means such as prior knowledge activation, self-explanations prompts, and compare and contrast activities. Students received the instruction by their regular class teachers. The teachers received a full day training provided by the authors of the study on how to use the instructional materials.

Knowledge Assessments

Before and after instruction, students answered a multiple choice questionnaire to assess their number of misconceptions (incorrect from a scientific view), everyday conceptions (partially correct), and scientific concepts (fully correct) about the floating ability of objects in water. The questionnaire has been developed in multiple pilot studies and has been shown to provide a reliable, valid and detailed method to assess conceptual knowledge about floating and sinking (see Hardy et al., 2006).

Before instruction, students additionally answered a questionnaire assessing the understanding of variable control (see Kuhn, 2002). The questionnaire consisted of 14 multiple choice questions (Cronbach's Alpha = .76). Some questions were adapted versions of classic tasks such as the ramp-task (Chen & Klahr, 1999) and the mouse-task (Sodian, Zaitchik, & Carey, 1991) and some were newly developed. All questions treated domains not related to the instructed topic. We used the sum score from the questionnaire as an indicator of students' basic experimentation skills.

Statistical Analysis

We used latent profile transition analysis, a type of latent transition analysis for continuous indicator variables, to statistically model the data. In a stepwise procedure, we first examined which knowledge profiles were present in the data. In discrepancy to Schneider and Hardy (2013), we allowed the number of profiles to differ between pretest and posttest, to examine the possibility that after instruction students have developed knowledge profiles that were not present before instruction. To decide on the number of extracted knowledge profiles, we relied on the Bayesian Information Criterion (BIC) that decreases with increasing model fit (Nylund, Asparouhov, & Muthén, 2007).

Next, we examined relations between students' experimentation skills and knowledge structure. We added students' experimentation skills to the analysis as a covariate to estimate their associations with profile frequencies before instruction. Finally, to scrutinize whether and how experimentation skills predict trajectories of knowledge development, we investigated their relation to students' transitions between the knowledge profiles from before to after instruction. Additionally, age was added to the analysis to control for its influence and to investigate potential interactions with experimentation skills. Due to the large sample size, we included the covariates directly into the model instead of using a stepwise approach (see e.g., Nylund-Gibson, Grimm, Quirk, & Furlong, 2014). Influences of experimentation skills on profile frequencies and profile transitions were interpreted if extreme groups (i.e., two standard deviations below the mean [-2SD] vs. two standard deviations above the mean [+2SD] on experimentation skills) differed more than 20% on the parameters. This number was chosen data-driven, as patterns above this cut-off stood out in comparison to the rest.

Results

Knowledge Profiles

Latent profile transition analyses were conducted to examine which knowledge profiles were present in the data. Information on model fit is provided in Table 1. The best model fit and theoretically most sound solution were obtained by extracting four profiles before instruction and six profiles after instruction (see Figure 1). Five of the six profiles were similar to the five profiles found by Schneider & Hardy (2013). Accordingly, we labelled the profiles following Schneider and Hardy. The "misconceptions" profile characterizes students with a high number of misconceptions but low numbers of everyday conceptions and scientific concepts, indicating a rather low proficiency level. The "fragmented" profile characterizes students with high numbers of all three types of conceptions, indicating a fragmented knowledge structure. In contrast, students in the "indecisive" profile show low numbers of all three types. Students in the "prescientific" profile show high numbers of everyday conceptions and scientific concepts, and those in the "scientific" profile show only a high number of scientific concepts, both indicating a rather high proficiency level. In addition, a sixth profile emerged that described children with a high number of everyday conceptions, labelled *everyday profile*. The scientific profile and the misconceptions profile were only present after instruction, indicating that instruction helped some students to develop an integrated conceptual understanding of floating and sinking, but also that some students did not benefit and even developed misconceptions.

Table 1: Model fit indices for the estimated models.

npro(t1)	npro(t2)	cov	npar	*ll*	*BIC*	*E*
1	1		10	-29631	59335	1
2	2		18	-29211	58552	.80
3	3		30	-28989	58196	.80
4	4		46	-28803	57941	.81
5	5		66	-28699	57878	.77
6	6		90	-28604	57862	.80
5	6		78	-28605	57778	.79
4	6		66	-28621	57722	.78
4	6	exp age	112	-28441	57697	.80
7	7		160	-28453	58070	.78

Note. npro(t1) = number of extracted knowledge profiles before instruction; *npro(t2)* = number of extracted knowledge profiles after instruction; *cov* = included covariates; *npar* = number of estimated parameters; *ll* = log-likelihood; *BIC* = Bayesian Information Criterion; *E* = Entropy (quality of profile separation). The finally chosen model is marked in gray, with four profiles before instruction, six profiles after instruction, and the covariates (experimentation skills [exp] and age) included.

Experimentation Skills and Profile Frequencies

Next, we controlled for age and included students' experimentation skills in the analysis to examine their associations with profile frequencies before instruction (see Figure 2). Adding the covariates led to a decrease in the BIC, indicating statistical significance (see Table 1).

With increasing experimentation skills from -2*SD* to +2*SD*, frequencies of the fragmented profile and the indecisive profile decreased from 35.7% to 12.3% and from 53.0% to 20.7%. At the same time, frequencies of the everyday profile and the pre-scientific profile increased from 10.4% to 36.4% and from 0.9% to 30.6%. These findings indicate that experimentation skills negatively relate to the frequency of inconsistent and less proficient knowledge profiles and positively to the frequency of more consistent and proficient knowledge profiles. Generally, these associations were stronger in older children, but also evident in younger children.

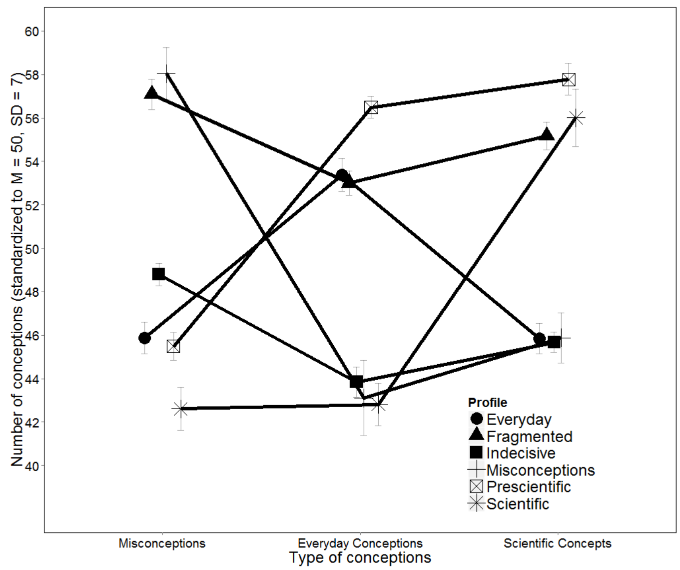

Figure 1: The six extracted knowledge profiles after instruction, represented by the number of different types of conceptions that students demonstrated. Symmetric 95% confidence intervals are depicted in gray. The misconceptions profile and the scientific profile were only present after instruction, all other profiles were present already before instruction.

Experimentation Skills and Profile Transitions

Crucially, experimentation skills influenced six transitions between profiles (see Figure 3). From before to after instruction, students with higher experimentation skills (+2SD) were less likely than those with lower experimentation skills (-2SD) to stay in the fragmented profile (+2*SD*: 19%; -2*SD*: 46%) or in the inconsistent profile (+2*SD*: 14%; -2*SD*: 54%). They were also less likely to change from the everyday profile into the scientific profile (+2*SD*: 1%; -2*SD*: 55.0%). In addition, they were more likely to change from the fragmented profile (+2*SD*: 62%; -2*SD*: 10%) or the everyday profile (+2*SD*: 47%; -2*SD*: 17%) into the pre-scientific profile, and from the indecisive profile into the scientific profile (+2*SD*: 61%; -2*SD*: 0%). Most of these influences suggest that students with higher experimentation skills are more likely to restructure their knowledge from before to after instruction and to change into more consistent and proficient knowledge profiles.

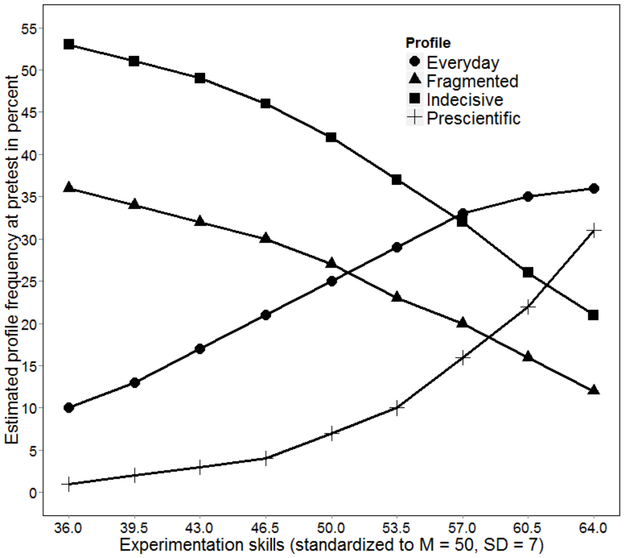

Figure 2: Associations between students' experimentation skills and frequencies of the four extracted knowledge profiles before instruction. With increasing experimentation skills from -2SD to +2SD, frequencies of the indecisive profile and the fragmented profile decreased, and frequencies of the everyday profile and the pre-scientific profile increased.

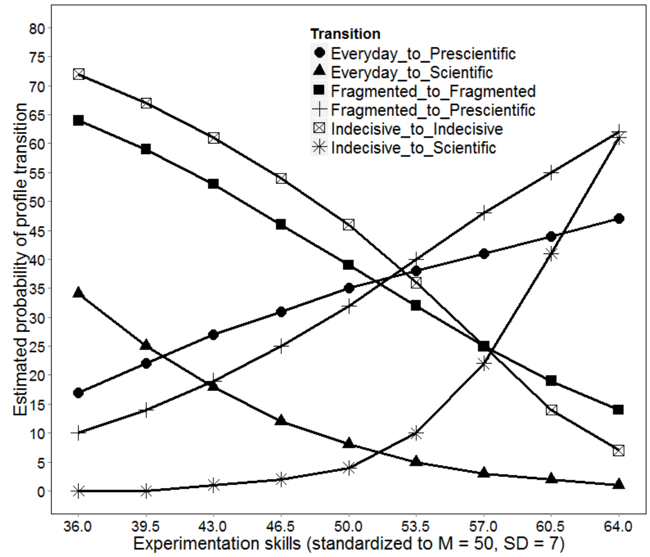

Figure 3: Experimentation skills and transitions between knowledge profiles from before to after instruction. With increasing experimentation skills, students are less likely to stay in the indecisive or fragmented profiles after instruction but more likely to change from the everyday profile into the scientific profile, from the fragmented profile and the everyday profile into the pre-scientific profile, and from the indecisive profile into the scientific profile.

Discussion

We examined the influence of experimentation skills on pathways of knowledge development in early science education. We assessed experimentation skills to predict knowledge development on the topic "floating and sinking", applying latent transition analysis on data from more than one thousand elementary school students. There are three main findings.

First, we could replicate the five knowledge profiles that Schneider and Hardy (2012) found in a smaller sample. In our sample of elementary school students from a broader range of grades, we found profiles similar to those described by Schneider and Hardy. In addition, we found a sixth profile that characterizes students with a high number of everyday concepts. These results validate the generalizability of Schneider and Hardy's findings from Germany across samples, grades, and countries.

Second, before instruction, students with higher experimentation skills showed decreased frequencies of the inconsistent and least proficient knowledge profiles and increased frequencies of the more consistent and proficient knowledge profiles. This is a correlational finding, corroborating the positive interrelation between cognitive skills and conceptual knowledge in elementary school students.

Third, children with higher experimentation skills were less likely to stay in the same knowledge profile from before to after instruction and they were more likely to change into consistent and proficient profiles. This finding supports the assumption that experimentation skills facilitate knowledge restructuring and integration, thus supporting successful conceptual change.

Unexpectedly, children with higher experimentation skills had a decreased likelihood to change from the everyday profile into the scientific profile. This finding might be related to the small number of children with lower experimentation skills who started in the everyday profile but it might also indicate difficulties to get rid of everyday concepts in the course of instruction.

To the best of our knowledge, our study is the first to relate experimentation skills to conceptual change using elaborate statistical models. In the teacher-guided inquiry provided in the study, a better understanding of variable control may have supported students in linking results from experiments to inferential conclusions. For example, if one wooden block floats but another another wooden block with identical size does not, students who understand that the experiment varied one thing at a time might infer that different kinds of wood indeed have different floating abilities, since all other factors were controlled. This finding complements fine-grained analysis on this issue obtained from microgenetic designs (cf. Schauble, 1990, 1996).

The present results suggest that to promote elementary school students' learning from inquiry-based instruction, teachers should ensure basic understanding of experimentation beforehand. Experimentation skills can be directly trained with relatively low time investment (e.g., Chen & Klahr, 1999) as a preparatory activity in science curricula. However, it is important to note that scientific reasoning, including experimentation skills, is confounded with general reasoning ability (Mayer, Sodian, Koerber, & Schwippert, 2014). Future studies are needed to investigate the interplay between experimentation skills and general reasoning ability in science learning, and whether the training of experimentation skills indeed promotes conceptual change in subsequent inquiry-based instruction.

We found latent transition analysis to be flexible and informative to tackle research questions and evaluate theoretical assumptions related to conceptual change. In our study, we extended the approach used by Schneider and Hardy (2013) by adding covariates to the models. Thereby, we could show that the profiles they extracted did not merely represent sample artifacts but actually relate to cognitive skills. Including covariates as predictors in the models provided detailed information on the influence of experimentation skills on knowledge development. We propose to use similar models also in future studies. Bayesian estimation might increase model flexibility and ease parameter estimation from smaller samples by incorporating information from prior studies into the models (see e.g., Chung, Lanza, & Loken, 2008).

Overall, the present study shows the predictive value of experimentation skills for describing pathways of conceptual change in early science education. Higher experimentation skills facilitate the development of proficient science knowledge with consistent structure, maximizing knowledge gains in early science education.

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