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Individual differences in the development of scientific thinking in kindergarten

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ABSTRACT

The present study examined the development of and individual variation in scientific thinking in kindergarten. We measured experimentation, evidence evaluation, and domain knowledge at two times in kindergarten (T1 and T2) in a sample of 100 five to six-year-olds. To explain individual differences, executive functions and linguistic abilities (grammar and vocabulary) were assessed one year earlier (T0). Executive functions and grammatical abilities predicted scientific thinking and its development from T1 to T2. Kindergartners grew in scientific thinking with evidence evaluation predicting the growth in domain knowledge. These results showed that evidence evaluation is important to acquire domain knowledge. Executive functions appeared to be a predictor of development in general. It is recommended that in early science education language should be taught in concurrence with scientific thinking in order to structure children's thoughts and guide their actions, as the present study showed that grammar predicted proficiency in experimentation and evidence evaluation.

1. Early development of scientific reasoning and domain knowledge

The primary goal of science education is to teach children to think scientifically, which includes domain-general reasoning processes and domain-specific content knowledge (Klahr, Zimmerman, & Jirout, 2011). Scientific thinking is part of the so-called 21st century skills, which prepare children for participation in the knowledge society (Fischer et al., 2014). Domain-general scientific reasoning processes consist of three core components: hypothesis generation, experimentation, and evidence evaluation (Klahr, 2000). Domain-specific content knowledge includes knowledge about domain-specific topics, such as physics and mathematics (Klahr et al., 2011). A common instructional method to increase scientific thinking is to have children gain knowledge about scientific domains via scientific inquiry (Zimmerman, 2007). However, this is only feasible when children know how to generate and test hypotheses (National Research Council, 2012). It has recently been shown that children as young as 4–6 years old (i.e., kindergartners) already can design unconfounded experiments with multiple variables (Van der Graaf, Segers, & Verhoeven, 2015) and are able to evaluate various types of evidence (Piekny, Grube, & Maehler, 2014). Concerning individual differences, executive functions and linguistic abilities appear to predict experimentation and evidence evaluation in kindergartners (Van der Graaf, Segers, & Verhoeven, 2016). Furthermore, young children's experimentation abilities (age 6 to 13) predict their domain knowledge about floating and sinking after a teacher-guided, inquiry-based intervention (Edelsbrunner, Schalk, Schumacher, & Stern, 2015). A similar role of evidence evaluation in predicting domain knowledge has not been evidenced yet. Furthermore, a longitudinal perspective on the individual variation in the development of scientific thinking in kindergarten is missing. In the present study, we therefore followed a cohort of 100 kindergartners across a period of two years, in an attempt to model (1) the developmental path to scientific reasoning and domain knowledge and (2) their interrelatedness, while (3) taking into account individual differences in cognitive and linguistic ability. The results of this study are relevant for educational practitioners, as assessment of the individual differences in the development of scientific thinking could inform them on how to optimize teaching of scientific skills and knowledge.

1.1. Development of scientific reasoning and domain knowledge

Scientific reasoning consists of three core components: hypothesis generation, experimentation, and evidence evaluation (Klahr, 2000). These components have been studied in children throughout primary and secondary school (see Zimmerman, 2007 for a review). The developmental perspective in Zimmerman's review is derived from cross-sectional studies with only few studies investigating scientific reasoning abilities in children at kindergarten age. After the 2007 review, little research on scientific reasoning has been conducted, and if so, it was

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mostly aimed at older children, such as the development from 9 to 13 years (Kuhn & Pease, 2008).

With respect to the first component of scientific reasoning, hypothesis generation, Zimmerman (2007) concluded that 10-year-olds often conduct experiments without explicit hypotheses, in contrast to 12 to 14-year-olds. Recently, kindergartners' ability to generate hypotheses was examined (Piekny & Maehler, 2013). It was found that these young children were not able to generate hypotheses in accordance with accumulating evidence that was presented. In addition, their performance did not increase from 4 to 6 years of age. Another cross-sectional study did show that there is improvement from kindergarten to first grade (age 6–7 years) on a question generation task (Jirout & Klahr, 2015, as cited in Jirout & Zimmerman, 2015). There was an improvement in recognizing what is unknown and generating a question to request that information.

Regarding the second component of scientific reasoning, experimentation, it has been shown that children aged 10–12 years old search less for possible experiments and produce less informative experiments than adults (Klahr, Fay, & Dunbar, 1993; Schauble, 1996). To produce an informative experiment, one variable needs to be studied at a time. When there are multiple variables, the Control of Variables Strategy (CVS) has to be applied. The CVS states that to investigate a single variable, one should design an experiment that controls all other variables, while manipulating the variable that is under investigation (Chen & Klahr, 1999). It has been found that children aged 10 years and older show understanding of the CVS and they can learn to use it more often (Chen & Klahr, 1999). Zimmerman (2007) notes that the CVS is slowly incorporated into the set of experimentation strategies as children become dissatisfied with the ambiguous evidence produced from non-informative experiments. This means that multiple experimentation strategies can coexist at one time. Recently, it has been shown that also kindergartners can understand the CVS (Van der Graaf et al., 2015). In this study, a dynamic assessment was used that consisted of providing feedback after each experiment based on the kindergartner's performance, so that they could learn during this task. The kindergartners were challenged to design an experiment with up to four different dichotomous variables in order to determine the effect of one of the variables. Almost half of the kindergartners designed experiments with three different variables correctly, indicating that they knew how to apply the CVS to design experiments. The difference in performance between the 4–5 year olds and 5–6 year olds in experimentation abilities, however, was large, which suggests that their experimentation skills develop in kindergarten. A longitudinal study of experimentation and evidence evaluation abilities indeed showed that these abilities improve in kindergarten (Piekny et al., 2014). Experimentation abilities were measured by asking the kindergartners about a single, dichotomous variable. The results revealed that kindergartners had problems choosing the correct setting in an experimental context, as their performance was around chance level at three points of measurement throughout kindergarten.

The final core component of scientific reasoning is evidence evaluation. Piekny et al. (2014) measured kindergartners' ability to evaluate various types of evidence. The evidence consisted of cards with a picture of a child on it. The child had either good or bad teeth, and was holding one of two colors of chewing gum. Multiple cards were presented to the kindergartners. The evidence could be conclusive (all cards point in the same direction), suggestive (most cards point in one direction) or inconclusive (when a conclusion cannot be drawn). The kindergartners' performance indicated that they understood how to evaluate the various types of evidence. The performance also increased when the children got older. Only the inconclusive evidence appeared difficult to evaluate, because even at the end of kindergarten, performance was around chance level. While Piekny et al. (2014) followed the kindergartners longitudinally, relations between experimentation and evidence evaluation abilities were not reported.

With respect to domain knowledge, or content knowledge, it is less clear what should be learned and when. However, four domains appear to be common in early childhood education as these were the topic of scientific research: plants and growth (Hickling & Gelman, 1995), floating and sinking (Hadzigeorgiou, 2015), sun and shadows (Chen, 2009), and paper planes (Guzey, Tank, Wang, Roehrig, & Moore, 2014). Kindergartners know that natural mechanisms underlie the growth of seeds and plants (Hickling & Gelman, 1995). They can also explain why objects float or sink based on the objects properties, such as weight, size, and material, but they have only an intuitive idea of density, which is needed to fully understand floating and sinking (Hadzigeorgiou, 2015). They can identify the moon and the sun and know what planets are (Vosniadou, 1991). Kindergartners also understand how to create shadows and most five-year-olds could predict shadows and their orientation correctly (Chen, 2009). They can also learn this in an exploratory way during a museum visit (Van Schijndel & Raijmakers, 2015). Young children can also identify variables that affect how straight a paper plane can fly (Guzey et al., 2014).

1.2. Relations between scientific reasoning and domain knowledge

An important issue in science education is the co-development of domain-general scientific reasoning abilities and domain-specific knowledge (Klahr et al., 2011). Scientific reasoning abilities are assumed to be domain-general abilities that can be applied in domain-specific contexts. Relations between the core components of scientific reasoning, i.e. hypothesis generation, experimentation, and evidence evaluation, have been found (e.g. Koerber, Mayer, Osterhaus, Schwippert, & Sodian, 2015) and these components may relate to domain knowledge (Zimmerman, 2007). However, experimentation and evidence evaluation appear to be unrelated in kindergarten (Van der Graaf et al., 2016). The study by Koerber et al. (2015) was conducted in an older age group (8- to 10-year-old children) and the authors used a questionnaire to measure scientific reasoning. It might be that the structure of scientific reasoning components is a function of age, if assessment format has no effect. It is yet unknown if and when the change from components to a single construct happens.

With regard to the relations of scientific reasoning with domain knowledge, scientific reasoning can be applied in order to acquire domain-specific knowledge (Zimmerman, 2007). A recent study investigated this assumption in a sample of six to 13 years old children (Edelsbrunner et al., 2015). They used a questionnaire to assess experimentation skills (i.e., CVS). The children were assessed on their knowledge about the floating ability of objects in water, before and after instruction. The instruction was teacher-guided and inquiry-based and it consisted of 15 lessons. The authors found that the experimentation skills predicted the proficiency and consistency of children's knowledge about floating and sinking (Edelsbrunner et al., 2015).

The reverse effect would be that domain knowledge could affect the quality of scientific reasoning. One consistent finding is that children bring their own ideas and preconceptions to the scientific activities. The instruction of how to use an object limited kindergartners' explorations of possible other functions of the object compared to naïve instruction or baseline (Bonawitz et al., 2011). Children, aged around 11 years old, showed a tendency to investigate the variables that were most consistent with their prior beliefs compared to adults (Schauble, 1996). This tendency has been shown to decrease from 10-year to 12-year-old, and even more so in 14-year-olds (Penner & Klahr, 1996). Because prior knowledge can affect scientific reasoning in different ways for different children, it is difficult to identify the effect of domain knowledge on scientific reasoning. As scientific reasoning is seen as a domain-general ability, which could affect domain knowledge acquisition, regardless of the domain, different domains should be used for investigating this effect. When the knowledge domain is different from the domain in which an experiment is carried out, the prior beliefs or preconceptions from the knowledge domain probably will not affect the scientific discourse.