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Benefits of “concreteness fading” for children's mathematics understanding☆

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ABSTRACT

Children often struggle to gain understanding from instruction on a procedure, particularly when it is taught in the context of abstract mathematical symbols. We tested whether a “concreteness fading” technique, which begins with concrete materials and fades to abstract symbols, can help children extend their knowledge beyond a simple instructed procedure. In Experiment 1, children with low prior knowledge received instruction in one of four conditions: (a) concrete, (b) abstract, (c) concreteness fading, or (d) concreteness introduction. Experiment 2 was designed to rule out an alternative hypothesis that concreteness fading works merely by “warming up” children for abstract instruction. Experiment 3 tested whether the benefits of concreteness fading extend to children with high prior knowledge. In all three experiments, children in the concreteness fading condition exhibited better transfer than children in the other conditions. Children's understanding benefits when problems are presented with concrete materials that are faded into abstract representations.

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1. Introduction

When we teach children a procedure for solving a mathematics problem, we not only want them to learn the procedure and apply it correctly, but also want them to understand why the procedure works. Indeed, a key question in the development of children's mathematical thinking is how we can help children gain understanding of underlying concepts from the procedures they are taught, so they can transfer those procedures beyond the specific, instructed context. Unfortunately, children struggle to gain conceptual understanding from a procedure, especially when it is taught in the context of abstract mathematics symbols (e.g., McNeil & Alibali, 2000; Rittle-Johnson & Alibali, 1999). Because understanding abstract symbols and manipulating them in meaningful ways are critical aspects of learning mathematics, the use of abstract symbols during instruction cannot and should not be avoided altogether. However, relatively minor changes to *when* and *how* abstract symbols are introduced during instruction may improve children's ability to extend their knowledge beyond the instructed procedure.

In the present study, we tested one hypothesized method for helping children extend their mathematical knowledge beyond a simple, instructed procedure: beginning with concrete examples and then explicitly fading to the abstract symbols. This “concreteness fading” technique is hypothesized to facilitate conceptual understanding by fostering knowledge that is both grounded in meaningful concrete contexts, and also generalized in a way that promotes transfer (e.g., Fyfe, McNeil, Son, & Goldstone, 2014; Goldstone & Son, 2005).

Students spend a lot of time learning and practicing mathematical procedures. For example, in representative eighth-grade math classrooms, students spent approximately two-thirds of individual work time solving problems using an instructed procedure (Hiebert et al., 2003). Unfortunately, students typically just memorize the procedure and rotely apply it as instructed. This leads to misunderstandings and failure to transfer the procedure appropriately. Indeed, children rarely benefit from procedural

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instruction, and correct transfer and conceptual understanding are low as a result (e.g., Matthews & Rittle-Johnson, 2009; Perry, 1991). For example, children often make "buggy" subtraction errors when they try to follow rules that they do not understand, such as changing a 7 in the tens place into a 5 in order to "borrow" two one's (e.g., Fuson et al., 1997). Similarly, children who learn a procedure for solving math equivalence problems with a repeated addend ($3 + 4 + 5 = 3 + \_\_$) often fail to correctly transfer that procedure to problems without a repeated addend ($3 + 4 + 5 = 2 + \_\_$; McNeil & Alibali, 2000).

One factor contributing to children's difficulties gaining conceptual understanding from procedural instruction may be premature reliance on abstract symbols. In fact, studies have shown that abstract symbols can interfere with understanding because they elicit the use of rote instructed procedures at the expense of informal, logical reasoning (e.g., Koedinger & Nathan, 2004). For example, children aged 9–15 were better able to perform math calculations when presented in a concrete context (e.g., "If I purchase four coconuts and each coconut costs $35, how much do I owe you?") than when presented in an abstract, symbolic context (e.g., $35 \times 4 = \_$; Carraher, Carraher, & Schliemann, 1985). In the concrete context, children used mental calculations of relevant quantities, whereas in the abstract context, children tried (unsuccessfully) to employ school-taught procedures. More generally, research suggests that abstract symbols can lead to inflexible application of learned procedures (McNeil & Alibali, 2005) and illogical errors (Carraher & Schliemann, 1985), neither of which indicate deep, transferable knowledge of mathematics.

One solution for helping children gain conceptual understanding from procedural instruction is to use concrete materials during instruction (e.g., blocks, balance scale). Such materials have several potential benefits. For example, concrete materials can activate intuitive, real-world knowledge during learning (Baranes, Perry, & Stigler, 1989; Kotovsky, Hayes, & Simon, 1985), enable learners to construct their own knowledge of abstract concepts (Brown, McNeil, & Glenberg, 2009), and prompt physical action, which has been shown to improve understanding and retention (e.g., Martin & Schwartz, 2005). However, the mere use of concrete materials does not guarantee success (McNeil & Jarvin, 2007). Indeed, although concrete materials may facilitate initial understanding, learners often struggle to apply that understanding beyond the instructed context. For example, numerous studies have shown that concrete materials hinder transfer to new, dissimilar situations (e.g., Gentner, Ratterman, & Forbus, 1993; Goldstone & Sakamoto, 2003; Kaminski, Sloutsky, & Heckler, 2008; Son, Smith, & Goldstone, 2011).

A promising alternative to using concrete materials alone to support conceptual understanding is to use them in combination with abstract symbols in a fading sequence. Specifically, many theorists recommend beginning with concrete examples and slowly fading to the more abstract (e.g., Bruner, 1966; Fyfe et al., 2014; Gravemeijer, 2002; Lehrer & Schauble, 2002). For example, Bruner (1966) proposed that new concepts and procedures should be taught using three progressive forms: (1) an *enactive* form, which is a physical, concrete model, (2) an *iconic* form, which is a graphic or pictorial representation, and finally (3) a *symbolic* form, which is an abstract, symbolic representation. The goal is to promote a rich, grounded understanding from instruction that is tied to conventional abstract symbols. In the present study, we use "concreteness fading" to refer to the specific three-step progression by which the physical instantiation of a concept becomes increasingly abstract over time.

Recently, McNeil and Fyfe (2012) provided support for concreteness fading. Undergraduates learned modular arithmetic using abstract symbols (e.g., pictures of solid black-on-white shapes), concrete examples (e.g., pictures of measuring cups), or a concreteness fading progressing. In the fading condition, the concrete elements and abstract elements were explicitly linked with an intermediate instantiation. Specifically, after learning with the concrete measuring cups, participants were told that the measuring cups would be represented by simpler symbols: I, II, III. After learning via Roman numerals, participants were told that any symbols could be used, and they were presented with the abstract elements. Students then completed a transfer test immediately, one week later, and three weeks later. Importantly, undergraduates in the fading condition exhibited the best transfer performance at all three time points.

Research by Goldstone and Son (2005) also provided some initial support for the "fading" hypothesis. Undergraduate students learned the scientific principle of competitive specialization via computer simulations that differed in their perceptual concreteness. The elements in the display either remained concrete (e.g., realistic ants and fruit), remained abstract (e.g., simple black dots and green shapes), switched from concrete to abstract, or switched from abstract to concrete. Going from concrete to abstract resulted in the most optimal transfer.

Despite these promising results, more research is needed. Neither of these studies included physical, concrete objects during the enactive stage as originally recommended by Bruner (1966). Further, neither progression fully explored the scope of abstractness. The concrete and abstract elements were both relatively concrete (i.e., pictorial images); the abstract elements were simply stripped of perceptual detail. It remains unclear if concreteness fading can improve understanding of conventional abstract symbols, of which learners may already have some misunderstanding. Finally, this prior research was limited to undergraduate students learning upper-level mathematical and scientific concepts. One study tested the benefits of concreteness fading for teaching fractions, but was limited to middle school students with mathematics disabilities. Butler, Miller, Crehan, Babbitt, and Pierce (2003) compared a full concrete-representational-abstract (CRA) sequence to a representational-abstract (RA) sequence. The CRA group used concrete manipulatives for the first few lessons, while the RA group used representational drawings. Students in the CRA group exhibited higher learning than students in the RA group.

Importantly, the "fading" method has yet to be applied in mathematics with typically-developing children in elementary school learning a specific procedure. Further, no study to date has tested the full three-stage fading method *and* included a rigorous control in which learners are exposed to the three stages in the reverse order. Finally, no study to date has explicitly examined whether the benefits of concreteness fading extend to learners with varying prior knowledge of the target concept. We addressed these gaps in the literature by examining the fading hypothesis in the context of children learning a procedure to solve math equivalence problems.

Math equivalence is the idea that two sides of an equation represent the same quantity, and it is critical to developing algebraic thinking (e.g., Falkner, Levi, & Carpenter, 1999; Knuth, Stephens, McNeil, & Alibali, 2006). Thus, it is an educationally-relevant and developmentally-appropriate topic for elementary school students. For example, the Common Core State Standards have included math equivalence as a first-grade standard (e.g., www.corestandards.org/ Math/Content/1/OA/D/7), and numerous studies suggest that children in first-through third-grade can learn to understand math equivalence (e.g., Baroody & Ginsburg, 1983; Davydov, 1969/1991; Jacobs, Franke, Carpenter, Levi, & Battey, 2007).

This domain is an apt domain in which to investigate whether concreteness fading can help children extend their knowledge

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