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Preschoolers use analogy to facilitate innovative problem-solving

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Abstract

Although children become adept problem-solvers early in life, creating tools to solve novel problems remains challenging throughout the early school years. To explore this problem, we gave one group of 4-7-year-old children (N = 25) the opportunity to compare multiple materials with matching functional properties across three trials. A second group (N = 26) saw the same materials in each trial. We considered whether children improved across trials and whether they transferred any learning to a new exemplar that required a different functional technique. Although children learned equally well across the first three trials regardless of condition, children who had the chance to compare materials were more likely to improve from the initial trial to the transfer trial. We discuss the implications for identifying the origins of innovative problem-solving.

Keywords: innovation; analogy; problem-solving; cognitive development

Introduction

Discovering new methods for solving challenging problems is at the core of innovation that has led to feats as diverse as space travel and cancer treatments. These new methods for overcoming these kinds of hurdles rarely result from a "Eureka" moment. Instead, they tend to rely on a variety of processes, including trial and error, rational thinking, and analogical reasoning. Investigating the origins of the capacity to creatively innovate and problem solve is important for identifying the mechanisms underlying discovery. In this study, we explore the role of analogical comparisons on innovative problem-solving in 4-to-7-year-old children.

Although the human species has demonstrated an exceptional capacity to innovate and problem solve, creative problem solving is not intuitive or automatic. Solving problems that have routine strategies laid out is much easier than forming new solutions to unique problems. This phenomenon is unsurprising when we consider our own experiences; following directions takes less effort and mental energy than finding a new solution to a problem. Empirical evidence also indicates that this is true developmentally. Young children learn to use tools, infer their intended use, and categorize them appropriately within the first two years of life (Horner & Whiten, 2005; McGuigan, Whiten, Flynn, & Horner, 2007). Despite the robust ability to problem solve and understand the nature of tool-use early in development, young children struggle to create their own tools for solving problems until about eight years of age. For example, in research by Beck and colleagues (Beck, Apperly, Chappell, Guthrie, & Cutting, 2011), 4- to 9-year-old children were required to retrieve a sticker from a bucket at the bottom of a tube. When given this task with a premade hook that can be used to retrieve the bucket, children can succeed at four years. In contrast, however, when children are given objects that have not yet been formed into the necessary tools (i.e., a pipecleaner that needs to be bent to form the hook), only at 8-9 years do children reliably spontaneously make a hook and succeed at this task without assistance (Beck et al., 2011). This stark contrast between capacity to use and create tools could stem from a variety of sources including cognitive and motoric limitations (Cutting, Apperly, Chappell, & Beck, 2014).

Research has only begun to explore the cognitive processes and developmental limitations that are involved in children's developing abilities to create new solutions to problems. Additional work examining 4- to 7-year-old's inability to invent a hook themselves indicates that a variety of cognitive factors that might be logical reasons children struggle with this task are not the source of the problem. For example, research indicates that children do not simply perseverate on a particular strategy (Chappell, Cutting, Apperly, & Beck, 2013) or fail to explore or understand the properties of the materials given to them in these tasks (Beck et al., 2011; Nielsen, Tomaselli, Mushin, & Whiten, 2014). The hurdle does not seem to be purely cognitive or physical: they have both knowledge about the causal functioning of hooks (Beck et al., 2011) and the physical capacity to make hooks (Cutting, Apperly, & Beck, 2011).

The fact that children succeed at this task both when given tools that are already formed and when shown how to form the functional tools (Beck et al., 2011) indicates that the creative aspect of considering how to solve a new problem is the missing piece. In a recent study, Beck and colleagues (2014) built upon evidence that 4-6-year-old children learn from being shown how to form functional tools (e.g., form pipecleaners into hooks). After children had seen demonstrations of how to form a hook out of a pipecleaner, the researchers asked whether children could transfer this knowledge to a similar task that differed in appearance. They found that, when children were given different colored pipecleaners and distinctly shaped buckets and tubes/boxes, they were able to transfer knowledge (i.e., that they could still bend a pipecleaner to solve the problem) from one demonstration to a new problem. This indicates that children can transfer their learning to closely related problems. The children struggled, however, when the materials presented required a different action in order to solve the problem. For example, after having seen a demonstration of bending a pipecleaner in order to create a hook, they were then presented with a wooden dowel that could be connected in order to create a hook. Although the goal and function were similar, children were unable to transfer their creative problem solving to this new task. Beck and colleagues have suggested that analogical reasoning (Beck et al., 2014) and executive functioning (Chappell et al., 2013) are likely to be critical for generalizing knowledge of tools to new situations and perhaps for creating new tools. This is because developments in children's reasoning skills are likely to help children draw upon their existing knowledge in novel situations and because executive function skills support complex planning and the implementation of these plans (Romine et al., 2004; Singer-Freeman, 2005).

The difficulty of transferring knowledge between perceptually dissimilar exemplars is not unique to this paradigm. In the literature on analogical reasoning, the difficulty of moving from close-transfer (e.g., recognizing similarities between two examples that differ only in color) to far-transfer (e.g., recognizing similarities between two examples that do not share perceptual features) is frequently discussed (Kotovsky & Gentner, 1996). Gentner (1988) has proposed that structural mapping, a domain-general capacity relying on comparisons between examples with matching relations, is key to overcoming the problem of transferring knowledge independent of perceptual features.

According to structure mapping theory (Gentner, 1988), comparisons between examples that share both perceptual and relational features facilitate this process. For example, in a study by Chen and colleagues (Chen, Sanchez, & Campbell, 1997), 10- and 13-month-old infants were given problem-solving tasks that required multiple actions to retrieve a toy. At 13 months, infants who first learned to solve the toy retrieval task with one set of tools and toys could transfer this learning to perceptually distinct tools and toys within a few trials (e.g., color/material of container, color of cloths, color of strings, and identity of toy changed across trials). In contrast, 10-month-olds only transferred learning between trials when either the goal (i.e., toy) or tools (i.e., cloth/string) were identical to that in previous trials. Similar effects of transferring novel actions based on matching goals has been found in subsequent research (e.g., Gerson & Woodward, 2013).

In the above-reviewed examples in the problem-solving domain, researchers found that perceptual similarities facilitate transfer across examples, consistent with the findings by Beck et al. (2014). They do not, however, directly test whether having compared these perceptually and relationally similar examples allow children to transfer this functional knowledge to new cases that are perceptually distinct.

Research in other domains, including categorization and spatial reasoning, provide evidence that close comparisons can facilitate far comparisons in some cases (Kotovsky & Gentner, 1996; Loewenstein & Gentner, 2001). For example, when three-year-olds have the opportunity to compare examples of rooms with matching layouts and identical furniture, they can subsequently transfer relational knowledge about the location of a hidden object (e.g., a bone is hiding under the couch that is next to the chair) to a room with a matching layout but perceptually distinct furniture. They cannot transfer this spatial relational knowledge without an opportunity to compare multiple examples.

This begs the question: Can children transfer learning from perceptually similar to perceptually distinct examples of innovate problem solving if they have the chance to make comparisons? In this research, we refer to the opportunity to make comparisons when children are presented with multiple examples that may be spontaneously compared based on similar functional relations. As far as we are aware, this has not been addressed in the domain of innovative problem solving. We directly test this hypothesis in the current research by combining the tool innovation paradigm previously used by Beck and colleagues (2014) and the structural comparison technique adapted by Gentner and colleagues in other domains (Gentner, 1998; Kotovsky & Gentner, 1996; Loewenstein & Gentner, 2001).

In the present study, 4- to 7-year-old children were presented with a sticker retrieval task like that previously used by Beck and colleagues (e.g., Beck et al., 2014; Chappell et al., 2013). In this task, children are presented with a sticker that is placed in a bucket at the bottom of a tube and are asked if they can retrieve the sticker. They are given a variety of materials with which they could attempt to solve the task. None of these materials, without adaptation, allow the child to retrieve the bucket, but some can be adapted in order to create a solution. As described above, for example, a pipecleaner can be bent into a hook in order to pull the bucket up by the handle. When children struggled with this initial task, they were shown a demonstration of how to solve the problem with the materials presented. In subsequent trials, children were either presented with physically similar materials (low alignability; e.g., other pipecleaners) or functionally matching but perceptually distinct materials (high alignability condition; e.g., a rubber wand that could be bent into a hook). Thus, in the High Alignability Condition, children had the opportunity to make a comparison between the materials and identify the critical functional aspects. Whereas in the Low Alignability Condition, the similarity between exemplars that was likely to be compared was about the perceptual, rather than functional, features of the tools. After three trials, children in both conditions were presented with distinct materials that required a different action to achieve the same goal (generalization trial; e.g., sticks that could be snapped together to create a hook).

Our analyses focused on the following questions:

1. Does comparing functionally similar items (High Alignability condition) lead to better transfer on generalization trials than using matching items (Low Alignability condition)?
2. Did improvement in initial trials (1-3) follow a similar trajectory across conditions?
3. Did improvement from the first trial to the generalization trial differ between conditions?
4. Are there age differences in performance and transfer between 4 and 7 years?

We hypothesized that allowing children the opportunity to make comparisons between functionally similar materials would be more beneficial for transfer to a different action than continuously using matching materials. We expected children to improve from trials 1-3 similarly across both conditions but expected the improvement on the generalization trial to be larger in the High Alignability Condition. Previous research suggests that children improve on these tasks from 4 to 6 years (e.g., Beck, Williams, Cutting, Apperly, & Chappell, 2016) and we expected to replicate the finding that children improve with age. The question of whether this improvement is apparent with or without comparison and generalization is exploratory.

Methods

Participants

Fifty-one children between the ages of four and six years participated in this experiment. Twenty-six children were assigned to the High Alignability Condition (HA; 21 females; mean age = 69.15 months) and twenty-five were assigned to the Low Alignability condition (LA; 14 females; mean age = 69.10 months). All children were recruited and tested at a local science museum in a mid-sized British city. The research was approved by a local ethics committee (EC.16.04.12.4498R). All parents completed written informed consent and children gave verbal assent.

Stimuli and Procedure

All children were shown a sticker inside a small bucket and told that they were going to play a game in which they needed to rescue a sticker. The bucket was dropped into a long tube and children were told if they could rescue the sticker, they could keep it (see Figure 1). After introducing the task, the experimenter placed an adaptable material (e.g., a pliable pipecleaner or connecting pieces that make a hook) and a non-adaptable material (e.g., a long stick) on the table and asked if the child could ‘get the sticker out using these things’. The experimenter then sat back and gave general encouragement to the child (e.g., ‘you’re doing great’) without providing any specific information. After one minute, if the child was unsuccessful, the experimenter demonstrated the solution. For example, she would bend the pipecleaner into a hook and use it to pull the bucket up by its handle until the bucket was raised off the bottom of the tube but did not quite reach the top of the tube. After the demonstration, the experimenter returned the tools to their original state (e.g., unbending the pipecleaner) and allowed the child an additional 30 seconds to attempt to retrieve the sticker.

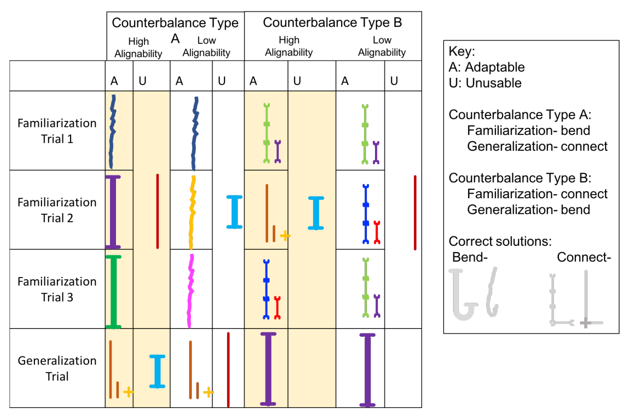

Figure 1: This figure depicts examples of the materials presented to children in each condition (and in the two counterbalancing cases) on each trial. It also demonstrates the correct solutions for each material type.

In trials two and three, children in the LA condition received similar materials for the adaptable item whilst the non-adaptable item only changed in colour. In the HA condition, children received a different material (e.g., the adaptable item could be a pipecleaner or a bendable wand, both of which could be formed into a hook). The procedure was identical to that of the first trial (with demonstrations occurring if child unsuccessful after one minute). Order of materials was counterbalanced across participants and conditions. In a generalization trial, children in both conditions received a novel set of objects that could be adapted in a different manner from that learned in the previous three trials (e.g., a stick with a connector piece that can be made into a hook). The entire session was videotaped from a profile view for offline coding.

Coding

For each trial, we coded whether children were successful at retrieving the sticker at each stage: prior to the experimenter demonstration and after the demonstration. For all presented analyses, success was measured as succeeding at retrieving the sticker prior to a hint or demonstration from the experimenter. We further coded whether children succeeded by using the expected techniques (e.g., bending the wand or connecting sticks) or by a different means. For example, although many children attempted to use a stick to pull the bucket handle up the side of the tube, most children were unsuccessful at retrieving the sticker using this method. Four children in the HA Condition and two children in the LA Condition, however, managed to succeed using this technique on one or more trials. They were therefore removed from further analyses because these children may have learned that they could succeed without learning the function of the tools. The coder also noted the time it took the child to retrieve the sticker on each trial.

Results

Initial analyses confirmed that patterns were similar across the two counterbalancing types, so all subsequent analyses were collapsed across counterbalancing types. We first investigated whether the proportion of children who succeeded on each trial prior to a demonstration or hint differed between the HA and LA Conditions. Children across conditions showed similar success rates in Trials 1-3, such that all children improved in their ability to successfully retrieve the sticker without a hint from the first to the third trial (see Figure 2). Although there was a descriptive trend in line with our hypothesis that children in the HA Condition would be more likely to succeed than children in the LA Condition on the fourth trial, this pattern did not reach significance (p = .18).

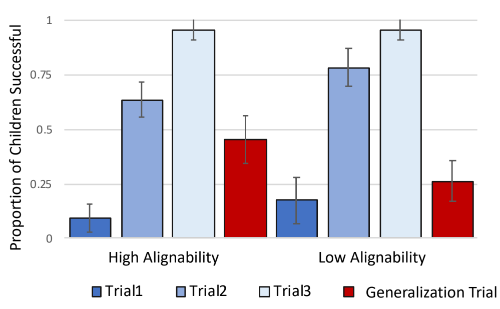

Figure 2: Mean proportion of children succeeding on each trial in each condition. Error bars represent standard errors.

As shown in Figure 2, within each group, the number of children who succeeded at the task without a hint increased from trials 1-3 and then fell again for the generalization trial. Descriptively, however, more children succeeded on the generalization trial than on the initial trial, suggesting that there may have been some benefit of learning. To examine this more closely, we first examined the number of children who succeeded versus failed to retrieve the sticker before a hint or demonstration was given on Trial 1 and the generalization trial in each condition. A McNemar test revealed that number of children who succeeded versus failed was significantly different between trial 1 and the generalization trial in the HA Condition (p = .021) but was not significant in the LA condition (p = .69).

We then examined the number of individual children who improved from Trial 1 to the generalization trial (i.e., children who did not succeed on Trial 1 but did succeed on the generalization trial) versus those whose performance did not change (i.e., children who were consistently successful or unsuccessful on both trials) and children whose performance decreased (i.e., children who succeeded on Trial 1 but failed on the generalization trial). A Chi square test assessing the difference between children who improved versus did not across the two conditions revealed a marginal effect such that children in the HA Condition were marginally more likely to improve than children in the LA Condition (see Figure 3; X^2 = 3.03, p = .08).

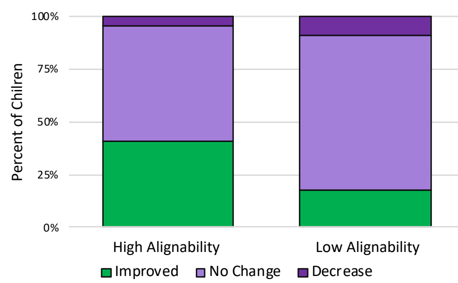

Figure 3: Proportion of children who improved (or did not) from the initial trial to the fourth trial split by condition.

In order to examine possible effects of age, we then created a median split based on age for each condition. The mean ages of younger children in the HA and LA Conditions were 4.84 (SEM = .23) and 5.06 (SEM = .22) years, respectively. The mean ages of older children in the HA and LA Conditions were 6.65 (SEM = .10) and 6.38 (SEM = .16) years, respectively. When reexamining the proportion of successful children (before a hint) across each trial, patterns looked similar across age groups (see Figure 4). No significant differences between age groups or conditions emerged, and the descriptive trend described above (better performance on the generalization trial in the HA Condition) appeared consistent across age groups.

Two additional Chi square tests were conducted to investigate whether improvement (or lack thereof) from Trial 1 to the generalization trial differed between conditions within each age group. No significant differences were observed in the younger children, χ^2 = .21, p = .65. The older children, however, were significantly more likely to improve in the HA than the LA Condition, $\chi^2 = 4.1$, $p = .04$ (see Figure 5).

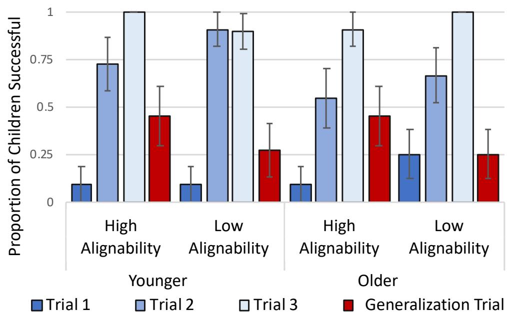

Figure 4: Mean proportion of children succeeding on each trial split into conditions and median split age groups. Error bars depict standard errors.

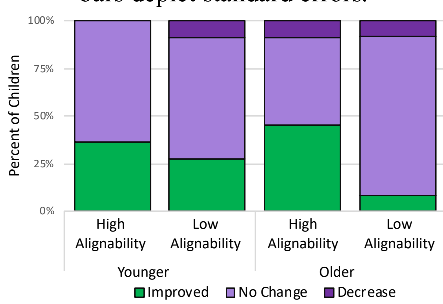

Figure 5: Proportion of children who improved (or did not) from initial to fourth trial split by condition and median age group.

Discussion

In this research, we investigated the role of analogical comparisons on innovative problem solving in 4- to 7-year-old children. Below, we restate our research questions and summarize our findings in relation to each of these questions.

1. Does comparing functionally similar items (high alignability condition) lead to better transfer on generalization trials than using matching items (low alignability condition)?

We assessed whether performance on the generalization trial differed between conditions and found no significant difference. Although the descriptive trend was in the expected direction, children were not significantly more likely to succeed without a hint on the generalization trial following the opportunity to compare functionally similar materials.

2. Did improvement in initial trials (1-3) follow a similar trajectory across conditions?

As expected, children improved between trials 1 and 3 in both conditions at similar rates. This suggests that children did not struggle to engage in close transfer when learning to innovate new solutions to a presented problem. It also indicates that any potential differences observed on the generalization trial were not due to a carryover from differences in success on trials 1-3.

Similar to past work (Beck et al, 2011; Nielsen et al, 2014; Whalley et al, 2017), 4-7-year-old children found it difficult to innovate a hook tool without a hint or demonstration on the first trial regardless of condition. However, their performance increased across trials 1-3, seemingly as they gained experience. Prior experience with a tool may influence children's tool making capabilities. Recent work has shown that prior experience of using or seeing a hook significantly improved the success of creating a tool in older (6-7-year-old) children and using a hook tool was especially beneficial for the younger (4-5-year-old) children (Whalley, Cutting, & Beck, 2017).

3. Did improvement from the first trial to the generalization trial differ between conditions?

In this analysis, we examined the proportion of children who failed to solve the initial problem without a demonstration and proceeded to succeed on the generalization trial relative to those who either solved the initial trial but failed to solve the generalization trial or maintained performance levels between these two trials. We found that marginally more children improved between trial 1 and the generalization trial in the HA than in the LA condition. This provides some evidence that analogical comparisons facilitated learning in this task, though the marginal nature of this effect warrants caution.

4. Are there age differences in performance and transfer between 4 and 7 years?

No main effects of age were apparent and, when split by median age, similar trends were observed across trials. When improvement from trial 1 to the generalization trial was assessed within each age group, a significant difference emerged in the older, but not younger, children such that older children were more likely to improve in the HA than the LA condition. This suggests that older children (around 6.5 years or older) were more likely to benefit from analogical comparisons than younger children. Prior work has shown that younger children are more likely to explore and older children show a conceptual shift in problem solving that allows them to create tools (Defeyter & German, 2003). Our results align with this prior finding, in that the older children were more likely to use analogy successfully to create a tool.

Although this research provides initial evidence that analogy is beneficial for innovative problem solving in children, the results must be interpreted cautiously due to marginal findings and relatively small sample sizes, particularly when analyses were divided by age group.

Future research should increase the sample size to examine more closely any potential differences between counterbalancing types (i.e., connecting versus bending actions learned/generalized) and age. A median split is a rough proxy of age and a larger sample size would allow a more fine-grained analysis of developmental changes in innovative problem-solving and use of analogical comparisons.

Additional avenues of future research include examining how children explored the materials before engaging in problem solving attempts. As discussed above, younger children tend to explore their environments more thoroughly than older children. Whether this means that younger children might be more likely to succeed on these tasks given more time is an empirical question. Further, previous research indicates that children are more likely to identify similar relations between examples when explicitly prompted to make comparisons (Christie & Gentner, 2010). One possibility is that drawing children's attention to the comparison to be made between, for example, pipecleaners and wands bending into hooks, would lead to stronger effects of analogical transfer.

Despite its limitations, the current research is an important first step in identifying the mechanisms that facilitate creative problem solving and innovation in children. The fact that improvements and transfer of learning was seen across both bending and connecting actions implies that the mechanisms are not unique to one instantiation of a problem. Identifying how and when children begin to transfer creative problem solving capacities to new and distinct problems is the gateway to unraveling and optimizing innovation.

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