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Tinkering to Innovation: How Children Refine Tools Over Multiple Attempts

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The human capacity for technological innovation and creative problem-solving far surpasses that of any species but develops quite late. Prior work has typically presented children with problems requiring a single solution, a limited number of resources, and a limited amount of time. Such tasks do not allow children to utilize one of their strengths: their ability to engage in broad search and exploration. Thus, we hypothesized that a more open-ended innovation task might allow children to demonstrate greater innovative capacity by allowing them to discover and refine a solution over multiple attempts. Children were recruited from a museum and a children's science event in the United Kingdom. We presented 129 children (66 girls, $M = 6.91$, $SD = 2.18$) between 4 and 12 years old with a variety of materials and asked children to use those materials to create tools to remove rewards from a box within 10 min. We coded the variety of tools children created each time they attempted to remove the rewards. By comparing successive attempts, we were able to obtain insights about how children built successful tools. Consistent with prior research, we found that older children were more likely than younger children to create successful tools. However, controlling for age, children who engaged in more tinkering—who retained a greater proportion of objects from their failed tools in subsequent attempts and who added more novel objects to their tools following failure—were more likely to build successful tools than children who did not.

Public Significance Statement

This study advances how we understand young children's problem-solving skills and capacity for innovation. Prior work has focused on whether children achieve an innovative solution or not; this study captures children's innovative process. Results demonstrate that children who decided to keep more objects from a prior design and who also added more novel objects to their tools following failure were more likely to build successful tools than children who did not.

Keywords: innovation, cumulative culture, problem solving, cognitive development

The human capacity for technological innovation and creative problem-solving far surpasses that of any species. Compared to other known tool-using species such as Corvids (Bird & Emery, 2009; Hunt & Gray, 2004) and chimpanzees (Whiten et al., 2005), humans build more tools for more purposes. Young children, however, are poor innovators. They fail to build simple tools when faced with simple problems (Beck et al., 2011, 2014; Carr et al., 2015; Cutting et al., 2011, 2014) and this seems to be a universal difficulty across several diverse populations (Gönül et al., 2018; Neldner et al., 2017, 2019). Below, we review several possible explanations for why younger children struggle to innovate and problem-solve and why they improve with age. We first discuss the role of cognitive abilities. We then discuss limitations in how past research assessed younger children's innovative capacities. We argue that prior work has not captured the full potential of children's innovative problem-solving capacities because it frequently focused on the outcome

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(whether successful innovation occurred) rather than the process of innovation (what children built and how they made adjustments over multiple attempts). Thus, the current study presented children with a problem-solving task with multiple solutions and focused on analyzing the process children use when innovating a successful or unsuccessful tool.

Technical Reasoning/Cognitive Abilities

Over the course of young and middle childhood, children are developing a suite of particular technical-reasoning skills that may enhance more sophisticated problem-solving (Beck et al., 2016; Osiurak & Reynaud, 2020; Rawlings & Legare, 2021). We theorize, along with others (Osiurak & Reynaud, 2020; Rawlings & Legare, 2021), that innovative problem-solving relies on multiple cognitive abilities working together rather than on a single cognitive ability or skill (Beck et al., 2016; Chappell et al., 2013). For example, causal reasoning is useful to help children think about how a tool can be built to achieve a desired effect (e.g., Gopnik et al., 2001; Legare et al., 2010; Neldner et al., 2017), analogical reasoning helps to apply and transfer knowledge across problems (Gentner et al., 2016; Gerson et al., 2018; Pauen & Wilkening, 1997), executive functioning skills help children use their prior knowledge to problem-solve (Pauen & Bechtel-Kuehne, 2016), and strategic information-seeking skills help children explore their environment with the explicit goal of testing and ruling out hypotheses (Kuhn et al., 1988; Ruggeri et al., 2016). Likely, the maturation of this suite of skills is necessary for complex problem-solving because it allows children to make better use of their prior knowledge and of their other cognitive skills (Garon et al., 2008; Miyake et al., 2000; Pauen & Bechtel-Kuehne, 2016). These skills allow children to represent and think about the problem they are trying to solve and to devise hypotheses about how to solve it.

Limitations of Prior Tasks Measuring Innovative Problem-Solving

One reason why research still lacks a clear understanding of the causes of children's poor innovative abilities may be that prior work examining children's innovative capacities has been limited to restrictive tasks that require convergent thinking (generating a single and correct solution to a problem; Beck et al., 2011; Hanus et al., 2011) rather than divergent thinking (generating multiple solutions to a problem; Evans et al., 2021; McGuigan et al., 2017; Weir et al., 2002). In a seminal experiment, titled the "hook task," 4-to-7-year-old children were asked to retrieve a basket with a sticker that was located at the bottom of a plastic tube (Beck et al., 2011). Children were given a string and two short sticks (non-functional tools) and a straight pipe cleaner (that children had to manipulate into a hook in order to retrieve the basket). Children were given one minute to solve the task. Children younger than 8 years rarely built a hook tool. However, when 5-year-olds were given the opportunity to have more time (up to 10 min) and were able to use other innovative strategies like detaching material from an object to make a hook, they succeeded more consistently (Voigt et al., 2019). In another classic experiment, the "floating peanuts task," 4-to-8-year-old children were given up to 8 min to retrieve a peanut from the bottom of a plastic tube (Hanus et al., 2011). Children had a pitcher of water next to the tube. Again, the oldest children were more likely to solve the problem than the younger ones by adding water to the tube thereby moving up the floating peanuts.

These results, that show young children struggle to create a successful tool, have been replicated across several studies and results consistently suggest that young children struggle to innovate tools and solutions to these novel problems (Beck et al., 2011; Cutting et al., 2011, 2014). There are several reasons that younger children may find these tasks more challenging. These tasks are limited in that they require children, in a *very short time frame* (but see Voigt et al., 2019) with *limited resource*s to solve a problem with *only one solution*. By requiring convergent thinking (assessing children's ability to focus on one narrow solution), these tasks did not allow children to take advantage of their remarkable ability to explore and to engage in divergent thinking. Moreover, this prior work has largely focused on outcome (whether children are or are not able to solve the hook or peanut task) rather than process (how children refine a solution to a task over subsequent attempts, but see recent papers by Evans et al., 2021; Voigt et al., 2019). As a result, we lack a clear understanding of *how* children innovate. Understanding this process may be key to better understanding how the various cognitive skills, theorized to impact innovative problem-solving, are involved at different points in development. And, maximizing children's innovative potential with a divergent task may illuminate children's exploration potential and provide insights into how contextual factors like the availability of various objects influence children's innovation capabilities.

Tinkering to Innovation

Young children are naturally curious and actively explore the world around them (Bijvoet-van den Berg & Hoicka, 2014; Gopnik & Wellman, 2012; Jirout & Klahr, 2012; Morris et al., 2013; Willard et al., 2019; Xu & Kushnir, 2013). Their play and exploration reveal an implicit sensitivity to uncertainty and the motivation to investigate further (Busch & Legare, 2019; Gweon & Schulz, 2011; Ronfard et al., 2021; Stahl & Feigenson, 2015). For example, children were more likely to explore and test a surprising claim than a claim confirming their intuitions (Ronfard et al., 2021). And, when children are surprised that an object no longer lights up a box, they are more likely to explore different solutions to figure out why (Legare et al., 2010).

In fact, in some cases, children appear to be more adaptable and flexible in their thinking and exploration than older children and adults. Younger children are much better at exploring a new environment and at coming up with different uses of objects than older children or adults (German & Defeyter, 2000). For example, 5-year-olds were not hindered by an object's preconceived function (a box that contained tacks) and used this object for a different purpose (to support a candle). Older children (aged 6 and 7 years) were more likely to be functionally fixed and to keep a box filled with tacks rather than use it for a different purpose. Other work has shown that children's exploration of objects can lead to better performance on tasks that engage divergent thinking (e.g., generating more solutions or exploration; Bijvoet-van den Berg & Hoicka, 2014; Dansky & Silverman, 1973).

These studies provoke an interesting puzzle: If young children are good at exploration and flexible in their thinking, why do they struggle to innovate? Based on the above-mentioned work, we propose that in order to innovate younger children may need to be able to *explore their way to innovation*. They need to be able to learn from their investigations and successive actions. If that is the case, then younger children's ability to engage in innovative problem-solving should be greater when assessed on more open-ended tasks that allow them to refine a tool over multiple attempts.

Thus, in this study, we examine the process of innovation in early childhood by coding children's exploration of tools and their progression of successes and failures during a problem-solving task. By doing this we hoped to track exploration and the way in which children explored and learned (or "tinkered") with the materials in order to solve a novel problem. Our first goal was to describe how children made adjustments to their designs over time: more specifically the extent to which children built upon their prior attempts (how much of a prior tool they retained on a later attempt) and how much they incorporated new elements in their designs. Our second goal was to examine whether such features of children's tinkering predict their ability to make a successful tool, controlling for age.

Current Study

The current study examines the links between exploration, tool creation, and creative problem-solving. Previous work examining innovation has largely focused on the outcome, such as the successful retrieval of a prize (Caldwell et al., 2016), thereby equating failure at a task as a lack of innovative abilities or ingenuity. As suggested above, these kinds of tasks do not typically allow children to have the opportunity to engage in divergent thinking and come up with multiple solutions. A recent study by Evans et al. (2021) gave 4-to-6-year-old children several different types of objects to use to retrieve a ball out of a jar. Their study showed that the type of exploration mattered for success on the task. Generating lots of tools did not influence success but when children were more purposeful in their exploration, these more iterative actions led to success. In the current study, and similar to Evans et al. (2021), we introduce a new task that allows children to come up with several solutions to solve the task by using multiple resources to create a tool (Figure 1). Instead of looking at specific actions, such as whether the manipulations were more functional (Evans et al., 2021) or the type of manipulation of a tool (e.g., detaching, reshaping) that better lead to success (Voigt et al., 2019), this study focuses on the successive process of how children explore objects, learn from this exploration, and use prior attempts to modify a tool to solve a task. More specifically (and as we detail below), we explored whether children who were and were not able to create a successful tool differed in their ability to tinker with a design—differed from one another in their tendency to exploit a prior design by keeping aspects of it and in their tendency to explore new solutions by adding novel components. Similar to Voigt et al. (2019), we also give children a lengthy period of time (10 min) in which to explore. Children received a clear box with plastic eggs (with sticker prizes inside) located at the bottom. The goal of the task was for children to construct tools to retrieve the plastic eggs, by grabbing or lifting them out of a hole located at the top of the box. We expect that a longer time period, access to different resources, and providing a more open-ended task provide the creative space for children to tinker and to utilize their ability to learn from exploration, to create and adapt tools, and to test out different plans to solve the problem.

The aim of this study is to explore the process of innovative problem-solving. We hypothesized that refining a tool after a failed attempt (tinkering) requires at least two components: (a) deciding what to keep from an existing design and (b) trying something new. In combination, these two components form what we term tinkering to innovation. Given that prior research has not examined this specific question and our approach may need to be refined in future research, we consider our results to be exploratory rather than confirmatory and hope that along with recent papers (Evans et al., 2021; Voigt et al., 2019), our results inspire more work on age-related changes in *how* children build and refine tools over subsequent attempts.

We operationalized "deciding what to keep from an existing design" as the percentage of objects children used on a prior failed attempt that they kept on a subsequent attempt. Over multiple attempts, a higher score on this measure indexes a greater tendency to keep objects making up a prior design than a lower score on this measure. We operationalized "trying something new" as the number of objects children had never used on prior failed attempts that children used on a new attempt. Over multiple attempts, a higher score on this measure indexes a greater tendency to incorporate new objects when refining a failed tool than a lower score on this measure. This coding scheme allows us to answer three questions: (a) Relative to prior research, are there age-related changes in children's ability to innovate on a more open-ended task with multiple solutions? (b) Are there any age-related changes in how children "tinker" with the tools they build over multiple attempts? (c) Controlling for age, do children who build successful tools approach building and tinkering with tools differently than children who do not build successful tools?

Method

Participants

A total of 129 children (66 girls) aged 4–12 years participated ($M = 6.91$, $SD = 2.18$) in this study. Children were recruited from the St Andrews Aquarium in Scotland, United Kingdom and a science engagement event at the University of Nottingham. All children spoke fluent English. Seventy-two participants volunteered information about their ethnicity. Most of the sample were White European (89%, $n = 72$) and the remainder were mixed (Asian, $n = 3$; Middle Eastern, $n = 1$; Mixed, $n = 2$; Black, $n = 1$, Other, $n = 1$). Ethical approval was granted by the University of St Andrews, approval code #PS12311 and by the University of Nottingham, approval code # F1075R.

Apparatus and Materials

The transparent box was 37 × 22 × 25 cm with an 8 × 8 cm window on top that was partially obstructed with a piece of tape to prevent children's hands from going inside the box (see Figure 1). Inside were three plastic eggs, each containing three different colored stickers. A string forming a loop was attached to the egg. This meant that children could retrieve the eggs by hooking the string or by picking up the eggs. At the start of the result section, we provide evidence that children did indeed retrieve the eggs using different methods. In front of the child were an array of objects that the child could use to manufacture a tool: straws of three different lengths, multiple pieces of sticky tape along table edge, a cup with two punched holes, connector cubes, two pipe cleaners, "Play Doh," and a small "egg holder" (a tool used for dying

Figure 1
Apparatus and Materials for the Tool-Building Task

Note. The transparent box was placed in front of the child (top left). The top of the box was partially obstructed to prevent children's hands from going inside (top right). Inside the box, we placed three plastic eggs, each containing three different colored stickers (bottom left). Building materials were placed in front of the child (bottom right). See the online article for the color version of this figure.

Easter eggs). There were duplicates of every item except for the cup, egg holder, and "Play Doh" (see Figure 1).

Procedure

Individual children sat at a small table where a box was centered in front of them along with all of the materials placed in front of the box. Children received these verbal instructions,

> Today you are going to play a game. See this box? See those eggs inside? In those eggs are prizes: stickers for you! (The experimenter then showed children an example egg and the sticker inside it). You are going to play by yourself. In this game you have to try to get as many prizes out of the box as you can by yourself. We'll count the total number of prizes you get at the end. You won't be able to reach the prizes with your hands; you'll need to figure out some other way to get them. You can use anything here that you'd like to use to make something to help you get the prizes. So, please come over here in front of the box and use these materials (Then experimenter pointed to all of the materials). Remember to try to get as many prizes as you can. Any stickers you find in the prizes you can keep! If you want to stop at any time, just tell me. I'm going to set the timer for 10 min. Are you ready to have a go? Ok..., go!

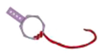
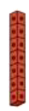
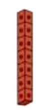
During the experiment, if children asked questions, the experimenter answered by saying, "It is a tricky task. You can use anything on the table to get the prizes out." When the child retrieved the three eggs or the timer went off after 10 min, children were allowed to open the eggs and keep the three stickers even if they had been unsuccessful. A video camera filmed children's actions directly in front of the child and at the level of the box so that all actions were visible and could be coded at a later time.

Coding

In order to understand how children modified tools over time, we first divided each child's interaction with the box into retrieval attempts. A child was coded as making a *retrieval attempt* each time a "tool" was entered into the container. Retrieval attempts were identified for each child until a child successfully retrieved an "egg" from the box or until time ran out. On average, children completed 7.13 retrieval attempts ($SD = 5.08$, $R = 1–27$). For each retrieval attempt, we coded *the number of objects* children used to build that tool. For example, the tool depicted in Table 1

Table 1

Tools Generated Along With How Each Tool Was Coded for Each Retrieval Attempt for a Randomly Selected 7-Year-Old Child Whose Last Attempt was Successful (Top) and a Randomly Selected 5-Year-Old Child Who Did Not Build a Successful Tool (Bottom)

Retrieval attempt	1	2	3	4	5	6	7	8	9	Average
7-year-old child										
Tool										
Successful	No	No	No	No	Yes					
No. of objects used	2	3	4	3	3					3
No. of novel objects used	2	1	1	1	0					1
% objects retained	—	100	100	50	67					79.25
5-year-old child										
Tool										
Successful	No	No	No	No	No	No	No	No	No	
No. of objects used	1	1	1	1	1	1	1	1	1	1
No. of novel objects used	1	1	0	1	1	0	1	0	0	0.56
% objects retained	0	0	0	0	0	0	0	0	0	0

Note. See the online article for the color version of this table.

(first attempt) is composed of two objects (a pipe cleaner and an egg holder). We did not keep track of children's manipulations of individual objects, for example, we did not code whether a child changed the shape of a pipe cleaner between retrieval attempts.

In order to capture variability in how children made changes to their tools over time, we coded, for each retrieval attempt after the first one, the presence of *previously unused objects* which allows us to measure children's tendency to incorporate new objects in their design and the *percentage of retained objects* which allows us to measure the tendency of individual children to retain objects they used in a previous tool rather than using new objects. For example, the first child in Table 1 (7 years old) used *a novel object*, an object they had never used before, on Trials 1, 2, 3, and 4 and used a total of five unique objects over five trials and thus an average of adding one novel object after each failed attempt (two different pipe cleaners, an egg holder, a short toy straw, and a medium toy straw). To code *the percentage of retained objects*, we counted the number of objects used by children in their current attempt that they also used in the prior attempt and divided that number by the number of objects children used in their prior attempt. For example, in Table 1, the tool built by the children on their first attempts was composed of two objects. On the next attempt, the child's tool was composed of those two objects in addition to a third one. Thus, the child retained 100% of the objects they used in the prior attempt and, on average retained 79.25% of the object they used on attempts following failure. In Table 2, we display the proportion of children who used each type of object. Inspection of Table 2, shows that children used many different objects and that they tended to use longer objects (like the long straw, cube connector, and pipe cleaner) more often than shorter objects like the short straw. Regressing the probability that children used each object type on age using logistic regression revealed no effect of age.

One research assistant naive to the research questions of the study, watched the videos and coded 100% of the data. Two additional research assistants also naive to the questions of the study coded 22% of the data (29 child participants). Interrater agreement for each code was excellent, all ICC > .96. The data from this study along with the statistical code used is publicly available on OSF (Burdett & Ronfard, 2022; https://osf.io/ejtvx/?view_only=494b28629f604117b67ebaa645b21498). We have also uploaded to OSF a set of online supplementary materials which includes our statistical output for each of the analyses we conducted. This study was not pre-registered and should be considered exploratory. However, our analyses were determined before we finished coding the videos.

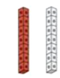
Results

We first describe the multiple solutions children came up with. We then examine the correlation between children's ability to build a successful tool and age. We then describe how children who did versus did not build a successful tool differed in (a) the number of attempts they completed, (b) the average number of objects they used on each of their attempts, (c) the average number of novel objects children used on each of their attempts, and (d) the average percentage of objects children retained from a prior attempt on their subsequent attempt. We then examine which of these factors predicts whether children built a successful tool, controlling for age.

Did Children Design Different Types of Tools to Retrieve the Prizes?

Our task was designed to allow children to be able to retrieve the eggs using at least two different methods: (a) children could remove the eggs by creating a hook and hooking the string loop attached to the eggs and (b) children could also remove the eggs by lifting the egg using the egg holder or the cup (see Figure 1). In Table 3, we display the different types of tools that children created. Inspection

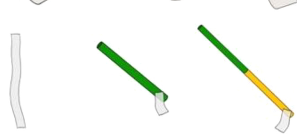
Table 2
Percentage of Children Who Used Each Object at Least Once

Long toy straw[a]	Medium toy straw[a]	Short toy straw[a]	Toy straw connector[a]	Tape	Pipe cleaner[a]	Plastic cup	Cube connectors[a]	Play Doh	Egg holder
									
94%	40%	30.%	60%	47%	69%	40%	64%	51%	63%

Note. Objects for which children had two exemplars ([a]) are counted as having been used if at least one of the exemplars was used. The probability that children used each object was unrelated to age, logistic regression, all *ps* > .064. See the online article for the color version of this table.

of Table 3 reveals that children did indeed come up with diverse ways of retrieving the eggs. In total, 70 out of the 129 children (54%) generated a successful tool (a tool that was able to remove an egg from the box). Of the 70 successful tools, 29 involved the creation of a hook (41% of successful solutions). These hooks were created in three different ways: by bending a pipe cleaner ($n = 14$), by adding a connector cube at the end of straw ($n = 13$), and by forming a hook by connecting straws with a connector cube to create a right angle ($n = 2$). Of the 70 successful tools, 17 tools were designed to scoop up the eggs (24%). These types of tools were created in two ways: by connecting an egg holder to a straw or cube connector ($n = 7$) or by connecting a cup to a straw, a cup to a cube connector, or a cup to a pipe cleaner ($n = 10$). Two other types of tools were created by children: 17 out of the 70 successful tools (24%) used tape to catch the egg and seven used straws or cube connectors as a long stick to catch the loop connected to the egg (11%). Table 3 provides the mean age of the children who created each type of tool, and how long it took children on average to create these tools (mean number of retrieval attempts and mean number of seconds). Mean age, mean attempts until creation, and mean time in seconds until creation did not differ significantly as a function of tool type based on three distinct ANOVAs (one for each outcome) with the between-subjects

Table 3
Categories of Successful Tools That Children Built Along With Examples of Each Type

Type of tool	Examples	Total no.	Age (years)	No. of attempts until creation	Time to creation(s)
Hook (pipe cleaner)		14	$M = 8.79$ $SD = 1.93$	$M = 4.21$ $SD = 2.97$	$M = 132.21$ $SD = 69.93$
Hook (connector cubes)		13	$M = 7.15$ $SD = 1.68$	$M = 4.62$ $SD = 3.40$	$M = 237.38$ $SD = 193.91$
Hook (straw)		2	$M = 7.5$ $SD = 2.12$	$M = 10$ $SD = 4.24$	$M = 238$ $SD = 107.48$
Egg holder		7	$M = 8\ .43$ $SD = 1.81$	$M = 5.86$ $SD = 3.44$	$M = 303.86$ $SD = 174$
Cup		10	$M = 8$ $SD = 1.76$	$M = 6.6$ $SD = 4.86$	$M = 313.2$ $SD = 105.95$
Tape		17	$M = 7.18$ $SD = 2.10$	$M = 5.06$ $SD = 5.23$	$M = 197$ $SD = 162.91$
Straw		7	$M = 9$ $SD = 2.45$	$M = 8.43$ $SD = 6.90$	$M = 308.43$ $SD = 221.22$

Note. Mean age, mean attempts until creation, and mean creating time did not differ significantly as a function of tool type. See the online article for the color version of this table.

factor of tool type (the seven categories presented in Table 2), all $ps < .07$.

Were Older Children More Likely Than Younger Children to Build Successful Tools?

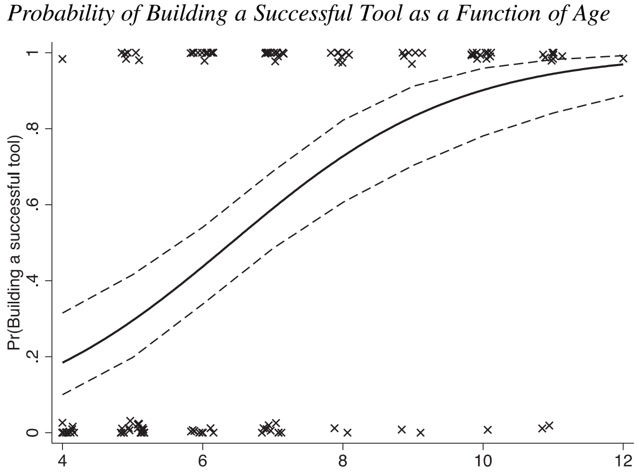
To examine the effect of age on whether children were able to build a successful tool (a tool that allowed them to retrieve one of the eggs), we regressed using logistic regression whether children were able (coded as 1) or were not able to build a successful tool (coded as 0) on children's age (in years). Consistent with prior research, older children were significantly more likely than younger children to build a successful tool, OR = 1.85, 95% CI [1.46–2.35], $z = 5.05$, $p < .001$ (Figure 2). On average, children who built a success tool were 7.92 ($SD = 2.00$) years old, while children who did not were 5.71 ($SD = 1.74$) years old.

How Did Children Who Ultimately Built a Successful Tool Differ From Those Who Did Not?

In order to identify how children who did versus did not build a successful tool differed from each other, we looked at four distinct measures. First, we looked at the number of retrieval attempts each of these groups completed. Second, we looked at the average number of objects each of these groups of children used on each of their retrieval attempts—a measure of tool complexity. Third, we looked at the average number of novel objects children used on each of their attempts—a measure of how many new object components children added to their tools after a failed attempt. Finally, we looked at the average percentage of objects children retained from a prior attempt on their subsequent attempt—a measure of how much children revised their tools, a higher percentage reflects smaller changes in the make-up of a tool across retrieval attempts. The means and standard deviations for each group for each of these measures are presented in Table 4. To test for significant differences, we used a t-test to compare children who did and did not end up building a successful tool on each measure. We also examined the correlation between age and each measure using a Pearson correlation, see Table 4. These analyses revealed that, on average, children who ultimately built a successful toy completed significantly fewer retrieval attempts, added significantly more novel objects to their tools after failure, and retained a significantly greater proportion of objects when making adjustments after a failed retrieval attempt than children who did not end up building a successful tool. No significant differences were found in the total number of objects these two groups of children used. Older children retained a significantly greater proportion of the objects making up their past tools when revising their tools after a failed attempt. This was the only significant correlation with age.

Figure 2

Probability of Building a Successful Tool as a Function of Age



Note. Dashed lines represent 95% confidence intervals. Model $\chi^2 = 37.88$, $p < .001$, pseudo $R^2 = .21$, $N = 129$.

Controlling for Age, What Predicts Whether Children Built a Successful Tool?

To look at how the various factors described above-influenced success, we conducted three logistic regression models. In the first one, we examined the effect of age on the probability that children created a successful tool. In the second model, we looked at the effect of tool complexity (the average number of objects children used on each attempt), the tendency of children to add new objects (the average number of previously never used objects children added on each attempt), and the tendency of children to retain aspects of their previous (failed) tool (the average percentage of objects of the prior tool they retained on the following attempt). In model 3, we added age and the number of attempts children completed as controls. We find that children were more likely to generate a successful toy if they used fewer objects overall, added a greater number of objects they had not yet used after a failed attempt, and retained a greater proportion of the objects making up the tool they created on a prior (unsuccessful) attempt, controlling for age and the number of attempts children completed (see Table 5).

Discussion

Young children are poor innovators. They fail to design simple tools for simple tasks. For example, they do not think to bend a straight pipe cleaner into a hook to grab a reward consistently until they are 7 years old (e.g., Beck et al., 2011). Such failures to innovate on the hook and peanut floating tasks have been replicated by multiple labs (Ebel et al., 2019; Gönül et al., 2021; Hanus et al., 2011; Nielsen, 2013; Voigt et al., 2019). However, one limitation of these tasks is that they require children to solely converge on a single solution and provide children with a limited number of resources. Thus, we hypothesized that a more open-ended innovation task with multiple solutions that allowed children to refine a solution over multiple attempts might allow children to demonstrate greater innovative capacities. In summary, we found that our open-ended task did not improve the task performance of the youngest children. Confirming prior work (Ebel et al., 2019; Gönül et al., 2021; Hanus et al., 2011; Nielsen, 2013; Voigt et al., 2019), we found that older children have more success compared to younger children. By implication, young children's failure in prior tasks is not due to their less open-ended nature. However, our open-ended task allowed us to examine a deeper analysis of the process of creative problem-solving and toolmaking. Notably, we found that successful innovators are strategic and purposeful "tinkerers" in their approach—they retain a greater proportion of objects they used in a prior (failed) tool

Table 4

Mean Number of Retrieval Attempts, Average Number of Objects Used on Each Retrieval Attempt, Mean Number of New Objects Added on Each Retrieval Attempt, and Average Percentage of Objects Retained From One Attempt to Another for Children Who Ultimately Did or Did Not Build a Successful Tool

Measure	Built a successful tool	Did not build a successful tool	Statistical test for difference	Correlation with age
Retrieval attempts	$M = 5.59$ (4.55)	$M = 8.97$ (5.14)	$t = 3.96, p < .001$	$r = -.10, p = .28$
Average no. of objects used	$M = 2.61$ (1.93)	$M = 2.37$ (1.43)	$t = 0.95, p = .35$	$r = .17, p = .05$
Average no. of new objects added	$M = 1.41$ (1.36)	$M = 0.97$ (.76)	$t = 2.20, p = .03$	$r = .10, p = .27$
Average % of objects retained	$M = 41.77$ (25.23)	$M = 32.12$ (27.11)	$t = 2.09, p = .04$	$r = .25, p = .004$

Note. Standard deviations are in parentheses. A successful tool was one that allowed a child to retrieve one of the eggs from the box. Of the children, 70 built successful tools, and 59 did not build successful tools.

and add more novel objects to their new tools. We discuss these results below.

Despite our task being more open-ended than prior tasks, we found a strong effect of age: 20% of 4-year-old children built a successful tool while close to 100% of 12-year-old children did so (Figure 2). In fact, the developmental trajectory—the age-related increase seen in Figure 2—is similar to prior work that used the hook (e.g., Beck et al., 2011) or floating peanut tasks (Hanus et al., 2011). In our task, younger children struggle to innovate even when presented with a task with multiple solutions, multiple resources, and more time. This also means that children do not fail to innovate because they lack experience with the causal affordances of the materials they were given (see also, Lew-Levy et al., 2021; Rawlings, 2022; Whalley et al., 2017). We gave them familiar materials and children's familiarity with those materials increased as they used them over multiple attempts and over a 10-minute period.

Although cognitive maturity is a clear advantage for success in creating a tool to solve a novel task, we also wanted to examine what other behaviors are important for toolmaking. Because of our open-ended design, we could further examine the process of innovation and creative problem-solving by comparing children who made successful tools to those who did not. By examining how children modified the tools they built following failed attempts, we gained new insight about the process of toolmaking. Two sets of findings emerged: (a) behaviors that supported innovation and (b) behaviors that changed with age.

By comparing children who did versus did not build a successful tool, we obtained information about the behaviors that supported innovation. We found that, on average, relative to children who did not end up building a successful tool, children who eventually built a successful tool used fewer objects, retained more objects from their failed tools on subsequent attempts, and added more novel objects to their tools following failure. This suggests that children who built successful tools used prior experience to tweak or "tinker" with their tool, to eventually make a useful tool to succeed at the task. Our analyses also revealed that with increasing age children retained more objects from prior tools. This suggests that part of what is developing over time and helping children innovate is the ability to tinker with a design—identifying what worked and what did not work and making decisions about what to keep and what not to keep. We return to this point below.

In our final analysis, we confirmed that the three aspects of children's tool-making process identified above predicted creating a successful tool, controlling for age and the number of attempts children made. Children were significantly more likely to create a successful tool if they used fewer objects overall, added more objects they had previously never used to their tools following failure, and retained a greater proportion of the objects they used on a prior (unsuccessful) attempt. This analysis also revealed that age still explained success even when controlling for these "process" behaviors. This supports the claim that successful innovation is unlikely to rely on a single cognitive ability and is instead supported by multiple cognitive abilities (Osiurak & Reynaud, 2020; Rawlings & Legare, 2021). Innovation is an ill-structured problem (Cutting et al., 2014): even though the goal is clear (e.g., retrieving the sticker) the means of reaching that goal are poorly specified. This aspect of innovation also helps to explain why children in our task struggled just as much as children tested on more closed-ended tasks (like the hook task). Whether a task has a single solution or multiple solutions does not make it any less ill-structured. In either case, innovating

Table 5

Logistic Regression Models Regressing Whether Children Built a Successful Tool

Variables	Model 1	Model 2	Model 3
Age	1.85*** [1.46–2.35]		1.99*** [1.47–2.70]
Average number of objects used		0.23*** [0.11–0.46]	0.27*** [0.12–0.60]
Average number of novel objects used		9.05*** [3.47–23.61]	4.86** [1.62–14.56]
Average percentage of prior tool retained		1.07*** [1.04–1.10]	1.05** [1.02–1.08]
Total attempts			0.88 [0.77–1.01]
Constant	0.019*** [0.004–0.094]	0.28* [0.10–0.76]	0.02*** [0.002–0.18]
Obs	129	129	129
Model χ^2	37.88***	34.90***	66.69***
Pseudo R^2	.21	.20	.37

Note. Coefficients are odds-ratios [95% CI]. CI = Confidence Interval; Obs = Observations.
$^{**}p < .01$. $^{***}p < .001$.

requires bringing to mind relevant knowledge, coordinating that knowledge, acting on it, reflecting, and making adjustments. Indeed, one of the predictors of innovation on our task, as well as a behavior that increased with age, was the extent to which children refined their design over time as indexed by an increase in the percentage of objects they retained following failure.

Of interest for future research is that this aspect of children's tool building echoes research on the development of children's exploration and scientific thinking (Gweon & Schulz, 2011; Jirout & Klahr, 2012; Ronfard et al., 2021; Willard et al., 2019; Xu & Kushnir, 2013). The youngest children in our study created a large number of (unsuccessful tools). We know from prior work that young children may be flexible in their thinking and can find different uses for objects (German & Defeyter, 2000). The youngest children may have been exploring the full landscape and resources, and using these tools to explore the causal effects of each object (Callanan et al., 2020; McCormack et al., 2015, 2016). Older children showed much more purposeful exploration (Ruggeri et al., 2016) characterized by retaining aspects of a prior tool. This suggests they are using prior knowledge to plan their next set of actions (Kuhn et al., 1988) and to create a better tool. The connection between innovation and scientific inquiry is worth thinking more about given that scientific inquiry and discovery are a form of innovation and are themselves ill-structured problems. It is not always clear how to best investigate new phenomena!

Our results suggest four next steps for research. First, future research can seek to link effective behaviors with particular cognitive skills. Past work seeking to identify the cognitive skills required for innovation examined correlations between these cognitive skills and whether children did or did not create a successful tool. As reviewed in the introduction, this approach has failed to provide clear data on which cognitive skills are involved. An alternative approach would be to examine which cognitive skills predict behaviors that have been shown to help the process of innovation. For example, which cognitive skills explain the retention of more objects after failure?

Second, future work could examine children's reflections on their tool-building experiences. Are children who are better able to reflect on what they did by highlighting the decisions they made better innovators? Moreover, given that asking children "why" questions helps them identify causal relations and their ability to problem solve (Walker & Nyhout, 2020), scaffolding children's innovation by asking them to explain their actions may help them innovate better.

Third, one limitation of our task is that we did not keep track of children's manipulations of individual objects, for example, we did not code whether a child changed the shape of a pipe cleaner between retrieval attempts. In future research, it will be important to keep track of these more minor adjustments to get a full understanding of how tinkering develops. Keeping track of major adjustments (as we did) as well as minor adjustments (which we did not do) would also make it possible to examine the association between these two behaviors. Two tentative predictions are that (a) children who make major adjustments also engage in minor adjustments (positive correlation) and (b) that major adjustments are likely to precede minor adjustments—major adjustments will be more likely to be found at earlier than later attempts while the opposite will be true for minor adjustments.

Fourth, our results suggest that children perform similarly on open-ended tasks and on convergent tasks. This suggests that the developmental challenge facing children is to come up with a solution and that the number of possible solutions itself does not matter. However, concluding from our data that task type (divergent vs. convergent) does not matter is premature. This is because our task, while open-ended, was still about removing an object from a container. Research needs to examine convergent and divergent innovation across different domains and task types to confirm that it does not make a difference. It would also be useful for future research to test the effect of task type using a within- rather than a between-subjects design. If additional research reveals that divergent innovation tasks are sometimes easier than convergent innovation tasks, how this difference manifests itself will be theoretically important. On the one hand, we might observe a main effect of task type. Divergent tasks may be easier for all children whether those children are younger or older. This would suggest that tasks that provide more pathways to success are simply easier and that innovation develops across childhood regardless of task type. On the other hand, we may observe an interaction between task type and age. Younger children may succeed on divergent tasks but fail on convergent tasks. This would suggest that the challenge of innovation in childhood is to come up with the "right" solution for the task. Given our results, the first option seems more likely. We look forward to what additional research will uncover.

Children have difficulty innovating tools to solve specific problems. This is true even when solving a problem could be accomplished by building various tools using different objects and when children are given the opportunity to refine their tool over time. Our results make two contributions. First, they clarify that children are particularly poor innovators when innovation requires combining or reshaping materials and objects to create a new solution. They appear to do better when they can innovate by subtraction than by addition (Voigt et al., 2019). Second, our results build on and extend those of Evans et al. (2021) by confirming that innovation success is not predicted by the ability to simply generate new solutions or by exploration alone. Rather, innovation requires deciding what to keep and what to add. It requires purposeful exploration (Evans et al., 2021). Our analyses of how children came to build successful tools highlight the importance of tinkering (the ability to decide what to keep and what to add) and opens up new avenues for research into how children solve the ill-structured problem of innovation.

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