Why do Children Lack the Flexibility to Innovate Tools?

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Abstract

Despite being proficient tool users, young children have surprising difficulty in innovating tools (making novel tools to solve problems). Two experiments found that 4-to-7-year-olds had difficulty on two tool-innovation problems, and explored reasons for this inflexibility. Experiment 1 (N=51), showed that children's performance was unaffected by the need to switch away from previously correct strategies. Experiment 2 (N=92) suggested children's difficulty could not easily be explained by task pragmatics or permission issues. Both experiments found evidence that some children perseverated on a single incorrect strategy, but such perseveration was insufficient to explain children's tendency not to innovate tools. We suggest children's difficulty lies not with switching, task pragmatics or behavioral perseveration, but with solving the fundamentally "ill-structured" nature of tool-innovation problems.

Keywords: Tool-innovation; Mental Flexibility; Ill-structured problems.

Human life revolves around the use of tools. It is almost impossible to consider life without them. How would we cook without pans and utensils? How would we even catch or dig up our food? Humans are believed to be experts in all tool-related behaviors (Defeyter & German, 2003; Herrmann, Call, Hernàndez-Lloreda, Hare, & Tomasello, 2007). However, despite extensive research indicating children's early competence for tool use, children's tool-making abilities have been neglected in the developmental literature. In this paper we distinguish between two types of tool-making: tool-manufacture – the ability to make tools after instruction or observation; and tool-innovation - independently making a novel tool to solve a problem. The present studies focused on children's tool-innovation, and explored whether children's difficulty with tool-innovation was due to mental inflexibility.

Early hominid tool use is thought to have propelled human evolution, making us the advanced social beings we are today (Csibra & Gergely, 2009; Kacelnik, 2009). Tool-related activities are implicated in the development of social behaviors such as imitation, teaching, and language (Csibra & Gergely, 2009; Gibson & Ingold, 1993). The Cultural Intelligence Hypothesis proposes that the advancement of these social capacities has allowed humans to develop cognitive skills not possessed by our nearest primate relatives (Herrmann et al., 2007). Our ability to collaborate and share knowledge permitted massive technological advances in our manufacture and use of an extensive range tools. Tools quite clearly have, and continue to play, an integral part in human life.

There is a substantial literature on the development of children's tool-related behaviors. Competent tool use is evident from an early age, demonstrated, for example, by the skilful manipulation of spoons (Connolly & Dalgleish, 1989), hooks and rakes (Brown, 1990), and many more tools in the second year of life. A large literature on social learning shows that young children are also able to learn about novel tools by imitating others from 2 or 3 years of age (McGuigan & Whiten, 2009; Meltzoff, 1995; Want & Harris, 2002). Young children can not only use tools, but show early abilities to infer their intended use (Casler & Kelemen, 2005), design (Casler, Terziyan, & Greene, 2009) and how they should be categorized (Defeyter, Hearing, & German, 2009).

Furthermore, a recent study has shown children to be competent in tool-manufacture (making tools after instruction) (Beck, Apperly, Chappell, Guthrie & Cutting, in press). Children as young as 3 years old readily manufactured a simple hook tool when the hook-making action was demonstrated. This is in line with the findings of research investigating infant memory for actions, which shows that at around 30 months children readily imitated a model who constructed a non-tool object e.g. a rattle (Hayne, Herbert & Simcock, 2003; Herbert & Hayne, 2000; Barr & Wyss, 2008). In this paper we explore a possible limit on children's excellent tool-related capabilities.

Tools were once thought to be a uniquely human phenomenon, but tool-related behavior is now widely studied comparatively. Recent research has focused on the making of tools. Chimpanzees *(Pan troglodytes),* have demonstrated the ability to manufacture a wide range of tools both in the wild (Boesch & Boesch, 1990), and in captivity (Bania, Harris, Kinsley, & Boysen, 2009; Visalberghi, Fragszy, & Savage-Rumbaugh, 1995; Povinelli, 2000). However, there is some debate as to whether such behavior, especially when seen in the laboratory, is insightful, or merely results from a trial and error approach (Povinelli, 2000).

New Caledonian Crows *(Corvus moneduloides)* are also well-known for their tool-manufacturing abilities. Specifically, they manufacture hooks from twigs to retrieve food in the wild (Hunt & Gray, 2002). More recently, impressive tool-manufacturing abilities have been seen in the laboratory. To retrieve a bucket from a tall narrow tube, one crow, Betty, bent a piece of wire into a hook, which she then used to solve the task. What was impressive was that Betty made a tool from a piece of wire, a material that crows would not encounter in the wild. Furthermore, on repeated trials she employed a variety of bending techniques, suggesting that her success was not the result of associative learning (Weir, Chappell, & Kacelnik, 2002). More recently, four rooks, a species that does not use tools in the wild, have also solved this tool-manufacture task (Bird & Emery, 2009).

Tool-Innovation.

Being able to make tools allows individuals to perform a much wider range of acts than they could without tools or with only found tools. However, we should remember that, in the corvid and child studies described above, when individuals make tools they have already seen an example of the required tool, and in the child study (Beck et al., in press) when children made tools successfully it was when the experimenter had even demonstrated how to make the tool. We term the ability to make tools having been instructed or having seen an example, tool-manufacture. This begs the question of where tools come from in the first place. Tool-innovation - making a novel tool to solve a problem - has been largely neglected by the comparative and developmental literatures. This is surprising because tool-innovation must be the foundation for all other tool-related behavior: children's (and adults') evident capacity to make tools and use tools that they see used by others would be of little use if nobody innovated tools in the first place.

There has been only one study to date of tool-innovation. Using an apparatus based on that used by Weir et al. (2002), Beck et al. (in press) investigated children's ability to innovate a simple hook tool needed to retrieve a bucket from a narrow vertical tube. Children were given a straight pipecleaner, a long piece of string, and some small matchsticks. The most obvious solution was to bend the pipecleaner into a hook. This is what most adults did when confronted by the task (a few individuals made a functional tool by attaching a matchstick to the pipecleaner to make an inverted "T"). The critical difference between this study and the studies with corvids (Bird & Emery, 2009; Weir et al., 2002) is that the child participants had not seen an example of the appropriate tool within the context of this task. Instead they had to imagine the solution themselves; that is, they had to innovate a novel tool. As mentioned above, when children in the same study saw the experimenter demonstrate making the appropriate tool, they had no difficulties repeating this tool-manufacture.

Children performed remarkably poorly on the tool-innovation task. Children aged 3- to 5- rarely made a hook, or any other functional tool; fewer than half of 7-year-olds succeeded; and children did not perform at high levels until the age of 9 or 10. These findings are even more striking in the context of further evidence presented by Beck et al. (in press). Even 4-year-olds understood that a hook was the best tool for the job and chose it over a straight pipecleaner significantly more than chance (Experiment 1). Children's difficulties persisted even after receiving a warm-up exercise with the materials that ensured they knew manipulation of materials was allowed and the pipecleaner is pliable (Experiment 3). Finally, the fact that tool-innovation was the limiting step for children was underscored by the finding that almost all children successfully completed the task when they received a demonstration of hook-bending after their initial failure. This is consistent with literature that shows children are very successful at social learning. The question that arises from this finding is why do children find tool-innovation so difficult?

Since young children clearly have the competence to manufacture and use tools, it seems unlikely that any difficulty with tool-innovation would be due to a lack of understanding of what tools are, or any difficulty with the practical business of shaping a tool and executing tool-using actions. Instead we look to a cognitive explanation. Difficulty with tool-innovation might be a consequence of the mental inflexibility that is commonly observed in early childhood. One way to characterize this mental inflexibility is to think about children's developing executive control.

Executive control is an umbrella term for psychological processes involved in the conscious control of thought and action (Zelazo & Muller, 2002; Anderson, 1998). Executive control is needed for novel tasks, or situations that require concentration, planning, strategy development, coordination, or choosing between alternative options (Diamond, 2006; Anderson, 1998; Brocki & Bohlin, 2004). Imagining what kind of tool is needed to solve a problem and how to make it (tool-innovation) is likely to tap many of these demands and to a greater extent than simply using or manufacturing tools, which rely mainly on imitating actions.

There are different ways in which we might construe the role of mental flexibility in tool-innovation. One possibility is that children are able to generate potential tool-innovation solutions to the task, but find it difficult to move on from unsuccessful ideas, and so tend to become "stuck in set". The ability to select and switch between multiple perspectives, tasks or strategies to determine the optimal option for the current situation is a well-known component of executive function that develops significantly between 3 and 5 years (e.g., Diamond, 2006; Chevalier & Blaye, 2009). This is demonstrated in simple card-sorting tasks (Frye, Zelazo & Palfai, 1995; Espy, 1997), where children begin to demonstrate the ability to shift flexibly between rules. Between the ages of 5 and 11 further improvements in cognitive flexibility occur, with children passing more complex tasks (Luna et al., 2001) and improving in speed and accuracy (Meiran, 1996). It seems plausible that difficulty with switching between alternatives might contribute to children's difficulty with tool-innovation.

Thus, in Experiment 1 we investigated the role of switching in tool-innovation. We tested children on two tool-innovation tasks that required 'opposite' solutions (hook-making required a pipecleaner to be bent; the new task required a pipecleaner to be unbent). We speculated that if children's difficulty was with switching between strategies then having succeeded (before or after a demonstration) using one strategy on one task, children might find it particularly difficult to adopt a different strategy on the second task. Furthermore, introducing a second tool-innovation task also allowed us to generalize Beck et al.'s claims, which were based only on a hook-making task.

A second possibility is that children have the capability to innovate the tools required for the tasks, but other features of our tool-innovation task created unintended difficulties, making it difficult for them to demonstrate this flexible behavior. For example, in the hook innovation task a straight pipecleaner is presented along with other distracter items as materials that can solve the task. Children may perseverate with the first material with which they attempt to solve the task and fail to switch to another material if the first proves unsuccessful. Alternatively, they may restrict themselves to using only unmodified materials rather than making them in to a new tool. We will discuss this further in the introduction to Experiment 2, where we adapt the task instructions so as to reduce the chances that children will perseverate with unmodified materials.

A third possibility is that, despite being able to make and use tools, young children lack the mental flexibility necessary to innovate tools because tool-innovation is an "ill-structured" problem. Executive function researchers distinguish between "well-structured" and "ill-structured" problems (Burgess, Alderman, Evans, Wilson, Emslie, & Shallice, 1996; Goel, 1995). Most commonly-used tests of executive function (including those used with children) are well-structured insofar as they have a clearly-defined set of stimuli (e.g., cards with colored pictures) a clearly-defined set of responses (boxes in which to sort the cards) and a clearly-defined set of rules (sort according to the color of the picture; then switch to sorting according to shape). In contrast, ill-structured tasks lack information either in their start or goal states or in the transformations needed to get from one to the other, and so part of the task requirement is for the participant to supply this for themselves. The difference between well- and ill-structured executive tasks is underscored by the observation that some brain-injured patients (Shallice & Burgess, 1991) and children with autism (White, Burgess & Hill, 2009) may pass traditional, well-structured, executive function tasks, yet show impairment on ill-structured tasks, and experience difficulties with mental flexibility in their everyday lives.

Tool-innovation is an excellent example of an ill-structured task. The participant has information about the start and goal states, but lacks information about how to get from one to another. They must devise and hold in mind a solution to the problem, inhibit irrelevant actions and plan a sequence of actions to achieve their goal. We return to whether tool-innovation might be thought of as an ill-structured task in the General Discussion, in the light of our tests of the role of cognitive flexibility.

Experiment 1

The first experiment replicated Beck et al.'s (in press) hook study, with the addition of a second tool-innovation task, unbending. In the new task a pipecleaner was presented bent in half and had to be unbent to make it long enough to push a ball from a tube. An unbending task was chosen as it requires the opposite action to the hooks (bending) task. Following Beck et al. (in press) children were given a piece of string as a distracter as well as a pipecleaner (although unlike Beck et al. we did not include small sticks, in order to prevent the making of other functional tools). The distracter material allowed us to see if the first material children selected was the functionally relevant pipecleaner. Also, all children received a warm-up exercise in which they manipulated materials (as in Experiment 3: Beck et al.) to ensure they had experience of the materials' properties. Although we did not explicitly check, all children were expected to have had previous experience working with pipecleaners in a craft context in school.

Method

Participants

The final sample consisted of 24 4- to 5- year olds (13 boys), mean age 4 years 10 months (4; 10), (range 4; 3 to 5; 3), and 27 6- to 7-year-olds (10 boys), mean age 6; 8 (range 6; 3 to 7; 2) from a Primary School in South Birmingham, UK. The ethnic composition of the sample was 91% Caucasian, 7% Black and 2% other/unknown. A further 5 children were tested but excluded from analysis, 3 children from the 6 to 7 age group retrieved the sticker without making a functional tool (e.g. by catching the bucket on the folded end of the wire pipecleaner) and 2 children from the 4 to 5 age group, one who retrieved the sticker without making a tool and one who had seen another child perform the task.

Materials

For the warm-up task a pipecleaner (length 29cm), pen (length 14cm), a piece of string (length 29cm) and a template of an S-shape printed onto A4 card (height 12cm, width 9cm) were used. For the hooks task the materials were a transparent plastic tube (height 22cm, width of opening 4cm) attached vertically to a cardboard base (length 35cm, width 21cm), a bucket with a wire handle, a pipecleaner (length 29cm), a piece of string (length

29cm), and a sticker (See Figure 1). For the 'Unbending' task the materials were a transparent plastic tube (length 22cm, width of opening 4cm) attached horizontally to a cardboard base (length 33cm, width 15cm), a pipecleaner bent in half (unbent length 22cm), a piece of string (length 29cm), and a small spherical pompom (like those used in crafts; diameter 4cm) with sticker attached (See Figure 2). We used a small clock to time the task.

Procedure

Before testing began children were instructed by their class teacher not to tell other children how to play the games they would be playing with the experimenter in order for them to be a nice surprise for everyone. Participants were tested by a female experimenter in a quiet area just outside the main classroom. The child and experimenter sat facing each other across a table. First, children completed the warm-up exercise. After this, all children received both the hook and unbending tasks. The order was counterbalanced across participants.

Warm-up task

Children watched as the experimenter demonstrated actions with the string and pipecleaner (order counterbalanced), which the child then copied. The pipecleaner was wound around a pen, and then removed to demonstrate that it kept its shape. The string was laid over the template to follow the S-shaped pattern.

Hooks task

Children were shown the vertical transparent tube with the bucket containing a sticker already in place in the bottom. They were told that if they could get the sticker out of the tube they were allowed to keep it. The experimenter then brought out the string and pipecleaner and told the child that these were things that 'may help' to get the sticker out. The children were then given one minute to try to retrieve the sticker. No feedback was given, but children were given neutral prompts if required. Examples of prompts used include 'Can you think how you might be able to get the sticker out?' and 'Maybe you could use these things to help you.' If, after one minute, the child had not retrieved the sticker, they were encouraged by the experimenter to put down the materials they were using. With the materials remaining on view in front of the participant, the experimenter then said 'watch this,' and using another pipecleaner held in the middle, bent one end to form a hook. The children were again encouraged to retrieve the sticker. They were not given the experimenter's hooked pipecleaner.

Unbending task

Children were shown the horizontal tube with the sticker attached to a pompom held in the middle. As in the hooks task, they were told that if they could get the sticker out they could keep it. The experimenter introduced the string and the bent pipecleaner as things that 'may help' to retrieve the sticker. If, after one minute had elapsed, the child had not retrieved the sticker, then they were encouraged to put down the material they were using. With the materials remaining on view in front of the participant, the experimenter then demonstrated 'unbending.' with another bent pipecleaner. The children were again encouraged to try to retrieve the sticker (using their own materials).

Measures

Children's behaviors were recorded online, using a coding system to differentiate their actions across time. The system coded materials selected (including whether they were touched, picked up, or entered into the tube), whether the material was manipulated and what shape was made, and whether the participant was successful before and after the experimenter's demonstration.

Results

There was no difference in success based on gender (Hooks – Fisher's Exact Test, p=.739, Unbending - χ^2 (1, N=51) =.123, *p*=.723), and so all data were combined for subsequent analyses.

As can be seen in Table 1 children did not assume all materials to be equally useful; there was a strong bias for children to both touch and use the pipecleaner first in each task. Furthermore, children tended to use the materials as they were presented and very rarely made any attempt to adapt them. However, as is clear in the final column of the table, once tool-manufacture was demonstrated, children easily succeeded in these tasks.

First we focused on the main variable of interest: successful tool-innovation before demonstration. Children were coded as successful in the hooks task if they bent the pipecleaner into a hook, within the one minute time limit, and used this to retrieve the bucket from the tube. Children were coded as successful in the unbending task if they unbent the pipecleaner (within the time limit) making it long enough to push the pompom from the tube. It was occasionally unclear whether unbending had been an intentional act as exerting force on the bent pipecleaner sometimes allowed it to unbend. As insight is difficult to establish all cases of unbending were coded as successful.

The low success rates before demonstration for the hooks task are consistent with Beck et al. (in press), demonstrating a stable finding that children display difficulties in innovating a simple hook tool. The new unbending task also yielded low success rates, with only a third of 4- to 5-year-olds and half of 6- to 7-year-olds unbending the pipecleaner to make it long enough to push the pompom from the tube. Since these results may include a small number of children who unbent the pipecleaner unintentionally, the results for true insightful tool-innovation may be lower still.

Comparison of success across age groups reveals a trend that older children successfully innovate more tools than younger children, but unlike Beck et al. (in press) we did not find a significant difference between age groups (Fisher's Exact Test, Hooks, p = .081; Unbending, p = .160). Therefore, data for the two age groups were combined for subsequent analyses.

Success before demonstration on the unbending task was better than on the hooks task (McNemar test, p = .011). We used Chi-square tests to investigate whether task order affected children's performance. Whether the hooks task was presented first or second had no effect on whether children succeeded in making a hook (Fisher's Exact Test, p >.999). Similarly order had no effect on success in the unbending task (χ^2 (1, N=51) = .167, p = .683). These results indicate that children's success on one task (whether spontaneous, or following demonstration) neither aided nor hindered their spontaneous success on the second task.

Having established there to be no relationship between behaviors between tasks, we decided to look more closely at both unsuccessful and successful (before demonstration) children's behaviors within each task. Although children were not perseverating on techniques across tasks, one possible reason for failure could be that children were perseverating on techniques within a task. We coded unsuccessful children as perseverators if they only ever entered one 'tool' into the tube and persisted in trying to retrieve the sticker with this 'tool' for the whole time period (1 minute). As can be seen in Table 2 perseveration was not a common occurrence for either the 4- to 5-, or 6- to 7-year-olds. Chi-square analyses show there to be no difference in perseveration between the two age groups (Hooks: $\chi^2(1, N=41) = .149$, $p=.699$; Unbending: Fisher's Exact Test, $p=.613$). Although it is a potential stumbling block to overcome if you first approach the task with the wrong 'tool', perseveration cannot explain why children are not successful in innovating tools in this study.

Although unsuccessful children rarely perseverated with one material for the whole time period, few manipulated the materials in any way, i.e. bent the pipecleaner or combined materials. In the hooks task only 18% of 4- to 5-year-olds and 26% of 6- to 7-year-olds manipulated materials, and similarly in the tube task the figures were only 25% (4 to 5 years) and 17% (6 to 7 years).

Next we examined the actions of successful tool-innovators within each task. Successful tool-innovators were coded as to the number of different items inserted into the tube before retrieving the sticker. Table 2 shows the majority of successful tool-innovators either entered a successful tool into the tube immediately (i.e. a hook or unbent pipecleaner), or entered one unsuccessful 'tool' (always an unmodified material) before making and entering a successful one. These results suggest tool-innovation resulted more from insightful solving of the task, rather than trial and error learning.

Experiment 2

In Experiment 1 children's difficulties in tool-innovation were shown to extend beyond hooks to another task: unbending. Investigation of children's success showed there was no effect of task order, which indicates that children's inflexible behavior on one tool-innovation task was not modified by a prior experience of making a tool on another task. Importantly, children's inflexibility did not appear due to perseveration on one unsuccessful strategy. Unsuccessful children in both tasks rarely perseverated with the same material for the whole time period. However, it was also notable that unsuccessful children made few attempts to modify the materials they were given. In our second experiment we explored the possibility that children may fail to modify the materials because they think that they are not allowed to.

Although children in Experiment 1 experienced a warm-up task in which they manipulated string and pipecleaner materials, it remains possible that these children did not realize that they were allowed to alter the materials given in the context of the main task. Alternatively, children may have failed to modify materials due to the pragmatics of the task. Children were presented with the materials as things that *'may help'* to retrieve the sticker. This may have been interpreted by children as the experimenter proffering the materials as tools that could be used *as presented* as a solution to the task, thus preventing modification. In Experiment 2, we sought to minimize the likelihood of permission or pragmatics playing a role in children's poor performance on the tool-innovation task by telling children they needed to make something with the materials.

Method

There were two conditions. In the control condition, children received the same instructions as in Experiment 1. In the experimental condition, children received the new instruction to *make something* with the materials. This instruction was used to avoid any assumption children may have had that the materials must be used as they were to solve the task. Also, we tried to reduce any possibility that children thought the experimenter was giving them pre-made tools to solve the task by introducing the children to a puppet that happened to have some materials with him. The aim of the puppet was to draw attention away from the experimenter; making the task appear more general rather than one which the experimenter had created and had the answer to. Because of this we excluded the warm-up phase of the experiment in which children completed an unrelated task that involved manipulating the materials. Previous results (Beck et al., in press: Experiment 3) indicated that the warm-up exercise had no effect on task success. The materials in the control condition were also presented by a puppet, and the wording changed to 'Here are some things that *can* help you.' We used the word "can" rather than "may" (as we had in Experiment 1) to match the certainty implied by the instructions in the experimental condition. Thus, the only difference between the experimental and control conditions was the instruction to make something.

Participants

The final sample consisted of 44 4- to 5-year-olds (17 boys), mean age 4; 10, (range 4; 5 to 5; 5), and 48 6- to 7-year-olds (25 boys), mean age 6; 10 (range 6; 5 to 7; 4) from a Primary School in South Birmingham. The ethnic composition of the sample was 48% Caucasian, 27% Black, 10% Asian, and 15% other/unknown.

Materials

The materials for Experiment 2 were the same as in Experiment 1 except for the addition of a short stick (5cm) presented as an additional distracter material (this matched the materials used by Beck et al., in press), a puppet, and a box (20cm x 13 cm x 5cm) in which the puppet carried the materials.

Procedure

Participants were tested in a similar environment to that outlined in Experiment 1. All participants received both the hooks and unbending tasks, order counterbalanced. Children were alternately assigned to either the control (help) group or to the experimental (make) group based on the teacher's class list. Children were introduced to the puppet, 'Heinz', and told 'Heinz really likes to play games, so he might come back later to see what we are doing'. The procedure for both groups was identical apart from the instructions given by Heinz.

Both the hooks and unbending tasks followed the same procedure as in Experiment 1, but after showing the tube apparatus, the experimenter exclaimed, 'Oh look here's Heinz; let's see what he has to say'. The experimenter then listened as Heinz spoke in her ear and then told the children either, 'Heinz says he has some things here that can help you to get the sticker' (control group) or 'Heinz says he has some things here you can make something with to get the sticker' (experimental group). As before, if the children had not retrieved the sticker after one minute, bending or unbending was demonstrated by the Experimenter.

Results

Examination of success rates showed there to be no effect of gender (Hooks - χ^2 (1, N=92) =.058, p=.809, Unbending - χ^2 (1, N=92) =.097, p=.755), and so all data were combined for subsequent analyses.

Both the hooks and unbending tasks showed the same pattern of behavior seen previously (see Table 3). Children had a strong bias to both touch and use the pipecleaner first, but very few then went on to manipulate the pipecleaner and innovate a tool.

This Experiment provides further evidence for the stability of the finding that young children do not readily innovate a hook tool to solve a task, with only 3 out of 44 4- to 5-

year-olds and 20 out of 48 6- to 7-year-olds innovating a hook to solve the task. The results for the new unbending task are also found to be consistent with the previous success rates, with 18 out of 44 4- to 5-year-olds and 34 out of 48 6- to 7-year-olds unbending the pipecleaner to retrieve the sticker. As in Experiment 1, the unbending task was easier for children to achieve than the hooks task, (McNemar Test, $p<0.001$). Chi-square tests were used to investigate whether task order affected children's performance. Whether each task was presented first or second had no effect on whether children succeeded in making a hook (χ^2 (1, N=92) = .000, $p>.999$) or unbending (χ^2 (1, N=92) = .003, $p=.956$), indicating the absence of transfer effects.

There was significant improvement in performance with age. Older children were more successful in innovating tools on both the hooks task (χ^2 (1, N=92) = 14.869, $p<0.001$), and the unbending task (χ^2 (1, N=92) = 8.365, $p=0.004$). Although no age difference was found in Experiment 1, age effects were observed in this age range by Beck et al (in press) and we conclude that the most likely reason for the difference between Experiment 1 and 2 is the larger sample size in Experiment 2.

The main aim of Experiment 2 was to test whether instructing children to make something with the materials helped them to be more flexible at innovating tools. Chi-square analyses revealed no difference between success rates for the Experimental and Control conditions for either Hooks (χ^2 (1, N=92) =1.174, $p=0.278$) or for Unbending (χ^2 (1, N=92) =0.057, $p=0.812$). This was also true for the two age groups independently (4- to 5-year-olds – Hooks: Fisher's Exact Test, $p>.999$; Unbending: χ^2 (1, N=44) =.376, $p=.540$: 6- to 7-year-olds – Hooks: χ^2 (1, N=48) =.861, $p=.353$; Unbending: χ^2 (1, N=48) =.034, $p=.853$). This suggests that it is unlikely that children's difficulty with innovating a tool is due to a mis-perception that they are not allowed to modify the tool-making materials.

As in Experiment 1 we then examined children's behaviors more closely (see Table 4). For unsuccessful participants we again coded whether they perseverated on one technique for the whole time period. Six- to 7 year olds' performance was consistent with Experiment 1. They did not perseverate with one object. In contrast, 4 to 5 year olds displayed higher levels of perseverative behavior. Chi-square analysis of the hooks task revealed 4 to 5 year olds to be significantly more likely than 6 to 7 year olds to perseverate on one unsuccessful technique for the whole time period ($\chi^2(1, N=69)= 13.511, p<.001$). This same trend was seen for the unbending task, but did not reach significance (Fisher's Exact Test, $p=.222$), most likely due to the lower number of unsuccessful participants.

Examination of the behaviors of successful tool innovators paints a similar picture to Experiment 1. In both tasks the majority of successful participants succeeded immediately or after just one unsuccessful insertion, suggesting a role for insight rather than trial and error learning.

General Discussion

The present experiments suggested that young children show striking inflexibility on two tasks that require them to innovate a simple tool, and investigated alternative reasons for this inflexibility.

An important first objective was to test whether difficulties previously observed by Beck et al. (in press) when children were required to innovate a hook tool would also be apparent on another task. Our novel "unbending" task was easier to solve than the hooks task, yet, overall performance was still poor. Around two-thirds of 4- to 5-year-olds and a third of 6- to 7-year-olds spent their time probing with inadequate materials rather than performing the simple action of unbending the pipecleaner needed to solve the task. A reason why the unbending task may be easier for children to solve could be because the final shape of the required tool is much simpler to manufacture than the hook. The fact that unbending is easier is consistent with research in the comparative literature that has shown chimpanzees have more difficulty assembling tools than disassembling them (Bania et al., 2009). In this study chimpanzees were given a tool composed of a long stick with two short sticks that could be added to each end to make an H-shape. Chimpanzees either had to assemble a hook to retrieve an object, or they had to disassemble the H-shape to form the long stick needed to probe in a tube. As stated above chimpanzees found it easier to disassemble the tool, which fits with our finding that children found it easier to unbend and therefore disassemble what they had been given, than they did assemble a hook. Further developmental research is needed to investigate different types of tool manufacture that may have differing levels of complexity.

Having established that tool-innovation difficulties are robust across two different tasks, we next considered whether the findings could be explained by children having difficulty with switching between possible task solutions. Experiment 1 revealed that in their second task children did not perseverate on techniques that had been successful in the first task. For example, children who, before the demonstration, successfully bent the straight pipecleaner to make a hook on their first task were just as likely to switch to the correct strategy of unbending for their second task, compared with children who did not bend the pipecleaner on their first task. However, it is also noteworthy that children did not demonstrate any positive transfer effects, meaning that succeeding or being shown how to succeed in the first task did not allow children to gain insight and facilitate their tool-innovation ability, and so did not increase the likelihood of success on the second task. This suggests that tool-innovation may not be an all-or-nothing insight that generalizes easily from one task to another.

Experiment 2 investigated whether children's inflexible behavior was due to a misunderstanding that they should not alter the given materials. By telling children they could make something with the materials we aimed to overcome any tendency for children to believe that the materials were things that should be used without modification. In fact, children who were prompted to make something were no more likely to make a tool than children who were only told that the materials "could help" with retrieving the sticker. Further evidence against the possibility that children thought they were not permitted to modify materials comes from the absence of transfer effects (in experiment 1) after the warm-up phase and (in both experiments) after their first task. Given that, in experiment 1, children modify a pipecleaner in the warm-up phase, and again when they either solve or are shown the solution to their first task, it seems even less likely that they still believe they are not permitted to modify the materials when they begin their second task. Yet, we observed no difference in children's levels of success between their first and second tasks. We believe that these considerations make it unlikely that task pragmatics or misunderstanding about permission to modify the materials are adequate explanations of children's tool-innovation difficulties. Nonetheless, it would be valuable for future work to include yet more explicit indications that the puppet or experimenter no longer needed the materials and that the child was allowed to change the materials.

To gain a better understanding of what children were doing within each task we analyzed the behaviors of both unsuccessful and successful participants. For unsuccessful participants we focused on perseverative behavior. Although perseveration was rare in Experiment 1, Experiment 2 yielded much higher perseveration rates for the younger, 4 to 5 year old children, with these children perseverating significantly more than the older children. As the levels of perseveration in each experiment are similar for the 6 to 7 year olds we suggest that the difference seen in the younger children is likely to be due to task differences between the two Experiments, rather than differences between the two samples. In this regard it is notable that in Experiment 1 all children received a warm-up exercise in which they manipulated the task materials whereas this was excluded from Experiment 2 in order to make the materials appear more incidental to the overall task. It is possible that the warm-up exercise in Experiment 1 helped the younger children avoid perseverative behaviors, perhaps by priming them to manipulate the materials given in the main task. However, despite this finding it is clear from our results that children's tool-innovation difficulties are not merely due to an inability to overcome such perseverative behavior. First, many children did not display perseverative behaviors yet were still not able to innovate tools. Second, for many of the children who succeeded, there was no apparent need to overcome perseveration on an initial unsuccessful solution because they immediately innovated successful tools. Nevertheless, although the current studies suggest that overcoming such perseveration is not the limiting step for tool-innovation success, the data do suggest that it may be a necessary condition for success. For if children initially use an unsuccessful 'tool' and then fail to stop using it, they can never go on to succeed in innovating a tool.

Together, then, Experiments 1 and 2 suggest that children's difficulty with tool-innovation may not derive from difficulty with switching between alternative tool-innovation solutions nor from difficulty overcoming a bias to view the tool-making materials as having pre-established, fixed functions. We can also rule out the possibility that difficulty arises from the need to overcome a tendency to perseverate with incorrect solutions. This raises the question of what other factors might lead to children's apparent lack of flexibility on tool-innovation tasks. One possibility is that, unlike many tasks examining the development of mental flexibility and executive function in young children, which are "well-structured" problems, tool-innovation is an intrinsically difficult, "ill-structured" problem (Shallice & Burgess, 1991).

To see why it might be appropriate to view tool-innovation as an intrinsically ill-structured task, it is useful to compare the tool-innovation tasks to a well-structured tool task. In Experiment 1 in Beck et al. (in press) children were given the same goal of retrieving a bucket containing a sticker from a deep, narrow container, but with the choice between a straight or a hooked pipecleaner. This is a well-structured task that has clear initial and goal states, and clearly defined strategies for how to move between them, and on this task children performed very well from the age of 4. Together with the evidence of children's success after the experimenter's demonstration of tool-making, this clearly demonstrates that children can recognize the solution to the problem when they see it, and can execute all of the relevant actions necessary to make and use the tool. What they find difficult is generating their own solution when it is not directly supplied.

A requirement to generate a solution that is not directly supplied by the task is the defining feature of "ill-structured" executive tasks. For example, in the Six Elements Test (Burgess et al., 1996) participants are presented with six tasks to complete and are asked to achieve as many points as possible by completing as many of the tasks as they can within a time limit, and whilst following rules, such as having to attempt every task. Thus, the task explicitly supplies the starting conditions (the games and the rules) and the objective (maximizing points scored on the games), but it is ill-structured because participants must devise their own strategy for tackling the problem. Such problems undoubtedly require multiple executive processes (including memory, inhibition, and switching), but as noted in the introduction, they do not seem to reduce simply to the sum of these components. It is possible to be impaired on ill-structured problems despite showing no impairment on standard, well-structured tests of executive function (e.g., Shallice & Burgess, 1991; White et al., 2009). We suggest that children's difficulty with tool-innovation may stem from the ill-structured nature of such problems. Although there is little evidence on the development of children's performance on ill-structured executive tasks, it is noteworthy that the ability to solve ill-structured tasks has been specifically associated with regions of medial prefrontal cortex (Brodmann area 10) that show protracted maturation throughout childhood and adolescence (Dumontheil, Burgess, & Blakemore, 2008). If children's difficulty with tool innovation is derived from a broader, domain-general, difficulty with solving ill-structured problems, then it would be expected that individual differences in performance at tool innovation should be correlated with individual differences in performance on other ill-structured problems in non-tool contexts, and this relationship should be independent of general intelligence and other executive functions, such as inhibition and working memory.

Alternatively, it could be that children's difficulty with generating structured solutions for tool innovation problems lies with a lack of domain-specific knowledge about the mechanical properties of tool-making materials, rather than with a domain-general problem with ill-structured tasks. If this were the explanation for children's difficulties with tool innovation then individual differences in successful innovation should correlate with other tasks that require knowledge of the mechanical properties of tools but do not require ill-structured problem solving. Moreover, such a correlation should persist even if children's performance on an ill-structured problem of another kind were partialled out. Future work would be necessary to distinguish between these possibilities.

Finally, whatever the detailed reason for children's difficulties, perhaps the most important conclusion from our studies is the simple and robust finding that tool-innovation is a difficult and late-developing ability. Even when children are excellent tool users and tool manufacturers they fail to innovate simple tools. It is often noted that children are excellent social learners (e.g. Csibra & Gergely, 2009). Our findings highlight the importance of social learning in children's developing ability to use tools, since "reinventing the wheel" for themselves is comparatively difficult. We might speculate that two factors were critical in the historical evolution of humans' tool-rich cultures. The ability to innovate tools is clearly vital for technological advancement, but it is equally important that the valuable products of this effortful process are preserved and passed on through social learning. Either of these abilities has the potential to be the limiting step on the development of tool-rich cultures. However, we venture that the capacity for cognitively demanding tool-innovation, rather than tool use, or tool manufacture, is what makes human tool culture stand out as uniquely complex.

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Table 1

Children's Behaviors during Innovation Tasks for Experiment 1.

	Touched first		Used first				**Success**	
Age Group	Pipe-cleaner	String	Pipe-cleaner as presented [a]	String	Pipe-cleaner adapted[b]	Combo [c]	**Before demo**	**Only after demo**
			Hooks Task					
4- to 5- *n=24*	21	3	20	3	1	0	**2** (8%)	**19** (79%)
6-to 7- *n=27*	25	2	23	1	2	1	**8** (30%)	**18** (67%)
			Unbending Task					
4- to 5- *n=24*	17	7	17	5	1	1	**8** (33%)	**14** (58%)
6-to 7- *n=27*	22	5	20	4	3	0	**15** (56%)	**11** (41%)

Note. [a]Hooks task: pipecleaner presented straight, unbending task: pipecleaner presented bent in half. [b]Hooks task: pipecleaner bent into hook, unbending task: pipecleaner unbent. [c]Subject combined string and pipecleaner, usually by tying them together

Table 2

Frequencies of perseveration in unsuccessful children, and number of insertions into tube for successful children for Experiment 1.

Age Group (years)	Unsuccessful			Successful			
		Perseveration			Insertion Into tube		
	N	No	Yes	N	Immediate Tool	1 unsuccessful then tool	2+ unsuccessful then tool
Hooks							
4 to 5	22	**15**	**7**	2	**1**	**1**	**0**
6 to 7	19	**14**	**5**	8	**2**	**4**	**2**
Unbending							
4 to 5	16	**13**	**3**	8	**2**	**4**	**2**
6 to 7	12	**11**	**1**	15	**3**	**7**	**5**

Table 3

Tool-innovation Behaviors as a Function of Age and Condition for Experiment 2.

			Touch First			Use first					Success	
Age group	Condition	N	Pipe-Cleaner	String	Match-stick	Pipe-cleaner as presented[a]	string	Match-stick	Pipe-cleaner adapted [b]	Combo [c]	**Before demo**	**After demo**
						Hooks						
4 to 5	Help	22	20	0	2	19	1	1	1	0	**1** (5%)	**19** (86%)
	Make	22	21	1	0	17	2	0	1	2	**2** (9%)	**17** (77%)
6 to 7	Help	23	21	2	0	19	3	0	1	0	**8** (35%)	**14** (61%)
	Make	25	23	1	1	17	1	0	4	3	**12** (48%)	**13** (52%)
						Unbending						
4 to 5	Help	22	14	7	1	11	7	1	3	0	**10** (45%)	**11** (50%)
	Make	22	16	2	4	11	2	4	3	2	**8** (36%)	**9** (41%)
6 to 7	Help	23	14	1	8	7	1	4	9	2	**16** (70%)	**7** (30%)
	Make	25	19	2	4	9	1	1	8	5	**18** (72%)	**4** (16%)

Note. [a]Hooks task pipecleaner presented straight, unbending task pipecleaner presented bent in half. [b]Hooks task pipecleaner bent into hook, unbending task pipecleaner unbent. [c]Subject combined string and pipecleaner, usually by tying them together. [d]1 participant in this group did not attempt to use a 'tool' and spent their time trying to make something.

Table 4

Frequencies of perseveration in unsuccessful children, and number of entries into tube for successful children for Experiment 2.

	Unsuccessful			Successful			
		Perseveration			Entry Into tube		
Age Group (years)	N	No	Yes	N	Immediate Tool	1 unsuccessful then tool	2+ unsuccessful then tool
Hooks							
4 to 5	41	**17**	**24**	3	**2**	**1**	**0**
6 to 7	28	**24**	**4**	20[a]	**7**	**8**	**3**
Unbending							
4 to 5	26	**19**	**7**	18[b]	**10**	**1**	**6**
6 to 7	14	**13**	**1**	34	**20**	**8**	**6**

Note. [a]Two participants retrieved the sticker without making a hook. [b]One participant retrieved the sticker without unbending the pipecleaner.

Figure 1. Apparatus used for Hooks task.

Figure 2. Apparatus used for Unbending task.

Figure 1. Tall tube containing bucket (with sticker inside), pipecleaner and string.

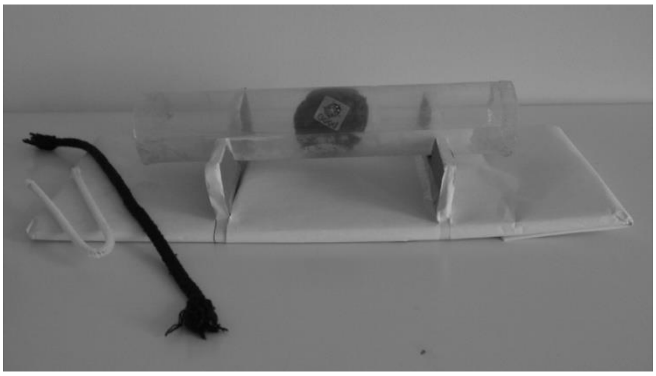

Figure 2. Narrow horizontal tube containing pompom (with sticker attached), bent pipecleaner and string.