The Puzzling Difficulty of Tool Innovation. Why Can't Children Piece Their Knowledge Together?

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Abstract

Tool innovation – designing and making novel tools to solve tasks – is extremely difficult for young children. To discover why this might be, we highlighted different aspects of tool-making to children aged 4 to 6 (N=110). Older children successfully innovated the means to make a hook after seeing the pre-made target tool only if they had had chance to manipulate the materials in a warm-up. Older children who had not manipulated the materials, and all younger children performed at floor. We conclude that children's difficulty is likely to be due to the ill-structured nature of tool-innovation problems, in which components of a solution must be retrieved and coordinated. Older children struggled to bring to mind components of the solution but could coordinate them, whereas younger children could not coordinate components, even when explicitly provided.

Keywords: Tool Innovation; Problem Solving; Ill-structured problems; Cognitive Development.

Tools are an essential part of human everyday life (Vaesen, 2012); it is hard to consider how we might get through the day without them. Tool-using capacity is evident from a young age, with children as young as 2-years using simple tools such as spoons (Connolly & Dalgleish, 1989) and rakes (Brown, 1990). Children gain the majority of their tool behaviors by observing others. As such social learning has been the focus of research into the development of children’s tool use (Flynn & Whiten, 2008, 2010; Lyons, Young & Keil, 2007; McGuigan & Whiten, 2009; Nielsen, 2006), and also their tool making (Beck, Apperly, Chappell, Guthrie & Cutting, 2011). However, social learning cannot be a sufficient explanation for the development of all tool making, because this would rule out the possibility of children (or anyone else) innovating novel tools (Nielsen, 2012). In contrast with findings when social learning is possible, recent findings suggest that innovation of novel tools, by which we mean creating a novel tool to solve a problem, is extremely difficult for young children (Beck et al., 2011; Cutting, Apperly & Beck, 2011). The focus of the current work was to determine what makes innovation so difficult. Our strategy was to highlight different components of the task solution to see if this improved children’s performance.

Children’s tool-innovation difficulties have previously been demonstrated in a series of experiments requiring children to innovate a tool in order to retrieve stickers (Beck et al., 2011; Cutting et al., 2011; Chappell, Cutting, Apperly & Beck, 2013). Children had great difficulty in generating the solution to bend a pipecleaner into a simple hook tool to retrieve a bucket from a narrow vertical tube. Children under the age of 5 rarely innovated a hook tool, and by the age of 8 only around half of children were successful on this task. This difficulty in tool innovation extends to making other tools using pipecleaners (Cutting et al., 2011), and to other materials and methods of tool making (Cutting, Beck & Apperly, under submission).

Children's difficulty with tool innovation is surprising as they appear to possess all the relevant knowledge required to solve tool-innovation tasks. Children are familiar with the properties of the materials, for example the pliant nature of pipecleaners. In previous studies children received manipulation exercises in which they bent pipecleaners prior to being given the tool-making task (Beck et al., 2011, experiment 3; Cutting et al., 2011, experiment 1). Practice with bending pipecleaners did not aid children on subsequent tool-making tasks. This suggests that if children did lack knowledge about the properties of pipecleaners (or other materials), then this is not sufficient to explain their difficulty.

As well as seemingly understanding the properties of pipecleaners and the fact that they are allowed to manipulate them, children also appeared to have the required knowledge about the physics of the problem they faced. In the hook task, children appeared to understand that a hook would be the most functional tool: in a tool-selection version of the task children as young as four years old chose the hooked tool over the straight tool first, when their task was to retrieve a bucket from a vertical tube using pre-made tools (Beck et al., 2011, experiment 1). Furthermore, children could also recognize a functional tool when shown how to make one: After initial failure on the hook-innovation task children readily manufactured a hook tool and used it correctly when shown a hook-making demonstration (Beck et al., 2011; Cutting et al., 2011). Note that children were only shown how to make the required tool; they were not given a demonstration as to how to use it.

Taken together this evidence suggests that it is not a simple lack of knowledge that limits children's performance. Children understand the properties of the materials they are given and are aware that they are allowed to manipulate them. Children understand the physics of the task and can recognize a hook as the most functional tool. So if children possess all of this knowledge why do they find tool innovation so difficult?

One possibility is that children's difficulty with tool innovation could be due to its ill-structured nature. Although there is no single agreed upon definition of what constitutes an ill-structured problem, a generally agreed upon framework is that an ill-structured problem is one that is missing information from its start state, goal state, or information regarding the transformation required to go between the two (Wood, 1983; Goel & Grafman, 2000). Following this definition tool innovation is an ill-structured problem: children are given the start state (the apparatus and the materials) and told that the goal is to retrieve the sticker, yet they are given no information regarding how they should go about this task. Compare this to Beck and colleagues' (2011, experiment 1) well-structured tool-selection task in which young children readily succeed. In this task children are given the start state (the apparatus and materials), the goal state (retrieve the sticker) and are given the choice between two possible means for effecting a transformation (use the straight pipecleaner or use the hooked pipecleaner). When information about the start state, goal and means were provided children found it trivially easy to retrieve the bucket.

Current findings suggest that just having all the individual items of domain knowledge is not sufficient to be successful in solving ill-structured problems (Chen & Bradshaw, 2007). Domain knowledge must be well-integrated into what is termed structural knowledge to enable people to utilize it effectively (Jonassen, Beissner & Yacci, 1993). Structural knowledge is knowledge that is well-integrated and developed and as such allows the person to use this knowledge in a flexible manner. This flexibility enables people to bring to mind the required pieces of knowledge and then successfully coordinate individual pieces of information into a useful solution. Some novices may possess all the relevant pieces of information, but only in experts is this knowledge integrated into structural knowledge that is flexible enough to solve the problem (Voss et al., 1986; Wineburg, 1998).

Applying this framework to tool innovation it is possible that although children undertaking these problems appear to possess all the knowledge required to solve the tasks, if this knowledge is not well integrated then they may still struggle to produce a solution. Children's difficulty in these tool-innovation studies may lie with bringing to mind the required pieces of information from memory, coordinating these different pieces of knowledge, or a combination of both.

From previous studies we know that highlighting the properties of the materials was not sufficient to elicit tool innovation. Four-to-seven-year-olds were not aided in making a tool when they were given bending practice which highlighted information about the properties of the pipecleaners (Beck et al., 2011, experiment 3; Cutting et al., 2011, experiment 1).We also know that just seeing the target tool that they were required to make, without any information regarding manipulation, was not sufficient to prompt children to make a tool for themselves (Cutting et al., under submission). This is particularly surprising given that children are able to see the utility of the end-state tool and select it to use themselves in the context of a tool-selection task (Beck et al., 2011, experiment 1).

In the current experiments we investigated whether children were able to coordinate information and successfully make a tool if we highlighted the properties of the materials *and* the target tool required. By highlighting property information to half of the children before they attempted the task and then providing all children with a target-tool demonstration after initial failure, we can begin to disentangle the minimum amount of information children require to successfully innovate a tool. Given previous findings we expected children who experienced bending practice to be no more successful in making a hook tool than children who did not receive bending practice. Second, if children failed to innovate in this first stage we then compared the two groups on their ability to make the tool following the target-tool demonstration. Based on findings from Cutting et al. (under submission) we expected children who did not receive bending practice to perform poorly following the target-tool demonstration. This would demonstrate children's difficulty with bringing to mind additional information. Examination of performance following the target-tool demonstration by the bending practice group would reveal whether children could successfully coordinate information. If the difficulty is in bringing information to mind, these children who have had information about properties and information about hooks highlighted for them should be more likely to solve the task. However, if children's difficulty is in coordinating information, even children who have had the information highlighted for them should still have difficulties with the task.

We tested children in the first (aged 4 to 5 years) and second (aged 5 to 6 years) years of compulsory education (UK) as these children perform near floor on previous tool-innovation tasks, and thus there was room for significant improvement.

Method

Participants

The participants were 53 children aged 4 to 5 years (24 boys), mean = 4 years 7 months (4;7), (range 4;1 – 5;1) and 57 children aged 5 to 6 years (26 boys), mean = 5;7 (range = 5;2 – 6;2) from two schools in the West Midlands, UK. Equal proportions of children from each school were present in each age group. The ethnic composition of the sample was 96% Caucasian, 3% Black and 1 % Asian. Participants had not taken part in previous versions of the task.

Materials

For the bending practice exercise, we used a pipecleaner (length = 29cm), a pen, a piece of string (length = 29cm), and a template of an S-shape printed onto card. Apparatus for the main task was a clear plastic tube (length = 22cm, width of opening = 4cm) attached vertically to a cardboard base (length = 35cm, width = 21cm), a bucket containing a sticker, a pipecleaner (length = 29cm) and a piece of string (length = 29cm) which acted as a distracter item (see figure 1). The experimenter used an identical pipecleaner (length = 29cm) for the demonstrations.

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

Procedure

Before testing, children were instructed by their class teacher not to tell other children how to play the games they would be playing with the experimenter to ensure they would be a nice surprise for everyone. All participants were tested by a female experimenter in a quiet area just outside the main classroom. The child and experimenter sat at right angles to each other at the corner of a table. Children were alternately allocated to either the bending practice or no bending practice group based on the teacher’s class list.

Bending practice exercise

Children in the bending practice group received the exercise prior to being given the main task. The exercise was designed to highlight the properties of the materials to the children, and was based on the procedure from Cutting et al. (2011). Children watched as the experimenter demonstrated actions with the string and pipecleaner (order counterbalanced), that the child then copied. The pipecleaner was wound around a pen, and then removed to demonstrate it kept its shape. The string was laid over the template to follow the S-shaped pattern. All children were able to perform the bending practice exercise.

Main 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 bucket out of the tube they could win the sticker inside it. The experimenter then brought out the string and pipecleaner and told the child that these were things that *'can help'* to get the bucket and 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 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 bucket, they were encouraged by the experimenter to put down the materials they were using. With the materials remaining in view in front of the participant, the experimenter then said '*look at this*,' and brought out a readymade pipecleaner hook for the child to view (target-tool demonstration). The children were again encouraged to retrieve the bucket using their own materials. If after 30 seconds the child had still not retrieved the bucket, they were told to put down their materials. With their materials remaining in view as before, the experimenter said '*watch this'* and taking her own straight pipecleaner, held in the middle, bent one end to form a hook (tool-creation demonstration). The experimenter did not demonstrate how to retrieve the bucket with the hook as previous studies have shown that such demonstration is not necessary (Beck et al., 2011). Children were again encouraged to use their own materials to retrieve the bucket. If children were still not successful in making a hook tool they were given verbal prompts such as '*Did you see what I did with mine?'* and then *'Can you do that?'* Thus there were three stages to the main task: Stage 1 after half the children had had the bending practice exercise. Stage 2 after all children had seen the target tool and Stage 3 after children saw the hook making action demonstration. Stages 1 and 3 largely replicated previous studies and so our main interest in this paper was performance in the two conditions at Stage 2. Children were coded as successful if they retrieved the bucket and sticker from the tube using a pipecleaner they had bent into a hook. Having made a hook, children did not require encouragement to use it.

Results

There were no effects of gender on level of success pre-demonstration χ^2 (1, N = 110) = 0.42, p = .518, φ = 0.062, or for success following the first target-tool demonstration, χ^2 (1, N = 97) = 0.64, p = .425, φ = 0.081, or second action demonstrations χ^2 (1, N = 54) = 0.05, p = .821, φ = 0.031. As such, data were combined across gender for subsequent analyses. The results were first analyzed for all children combined and then for the two age groups separately.

Overall 84/110 children were successful in making a hook tool at any of the three stages of the task. Children's success at innovating a hook during Stage 1 was examined to see whether the bending practice facilitated performance. Overall, children were very poor during their first exposure to the task, with only 13 out of 110 children successfully making a hook tool. Seven of these children were in the bending practice group and 6 did not receive bending practice, demonstrating no effect of condition, χ^2 (1, N = 110) = 0.05, p = .822, φ = 0.022. When we break this down into separate age groups, only 2 4- to 5-year-olds were successful, both of whom did not receive bending practice, showing no difference between conditions, Fisher's Exact Test, p = .236. For the 5- to 6-year-olds 7 of the successful children were in the bending practice group and 4 were in the no bending practice group, again showing no difference between conditions, χ^2 (1, N = 57) = 0.89, p = .346, φ = 0.125. Children who were successful on their first exposure to the task were excluded from subsequent analyses that compared success following the demonstrations.

Table 1. *Frequency of children's tool-making following different levels of instruction in Experiment 1.*

			Success			
Age Group (years)	Condition	N	Stage1: Before Demonstration	Stage 2: Following target-tool demonstration	Stage 3: Following tool-creation demonstration	Never Succeeded*
4 to 5	Bending practice	27	-	10	9	8
	No bending practice	26	2	6	10	8
5 to 6	Bending practice	29	7	18	2	2
	No bending practice	28	4	9	7	8

Note: * These children were verbally told how to complete the task. All children received the sticker.

Chi-square analyses were used to compare children's performance at Stage 2 following the target-tool demonstration. For both age groups combined, children were significantly more likely to make a hook tool following the target-tool demonstration in the bending practice condition than in the no bending practice condition, χ^2 (1, N = 97) = 6.59, p = .010, φ = 0.261. Comparison across age groups shows that older children were significantly more successful than younger children in the bending practice condition, χ^2 (1, N = 49) = 9.93, p = .002, φ = 0.450. No difference in success was seen in the no bending practice condition, χ^2 (1, N = 48) = .87, p = .350, φ = 0.135. When the two age groups were analyzed separately the difference in success between conditions was found to be driven by the older children, χ^2 (1, N = 46) = 9.30, *p* = .002, φ = .450 (see table 1). This suggests that 5-to-6-year-olds are able to coordinate the information if they received both the bending practice and saw a pipecleaner hook. No such difference was seen for the 4 to 5 year old children, χ^2 (1, N = 51) = 0.86, *p* = .355, φ = 0.129.

Children who were successful following the target-tool demonstration were excluded from the following analyses that investigated success at stage 3, which followed the tool-creation demonstration. For children requiring this demonstration 55% were successful at making the tool needed (see table 1). Chi-square analysis revealed no difference in the levels of success for each group following the action demonstration for either the 4-to-5-year-olds, χ^2 (1, N = 35) = 0.02, *p* = .877, φ = 0.026, or the 5-to-6-year-olds, Fisher's Exact Test, *p* > .999.

Discussion

In the current work we highlighted various aspects of the task solution in order to discover why children have difficulty with tool innovation. Information regarding the properties of the materials and an example of the tool children needed to create were highlighted. The current findings suggest a series of limiting steps in innovation, with children getting stuck at different steps at different ages.

Overall, we found that very few 4 to 6-year-olds spontaneously innovated a hook tool with either no additional information or just information about pipecleaner properties highlighted. These results are in line with previous research demonstrating that young children have great difficulty in innovating tools with either no additional information (Beck et al., 2011, experiment 2) or information highlighting pipecleaner properties (Beck et al., experiment 3; Cutting et al., 2011, experiment 1). It should be noted that success on this task has been shown to improve with age, with children becoming extremely proficient by the age of 9 or 10 (Beck et al., experiment 1).

The main aim of the current study was to test children’s ability to make a tool following a target-tool demonstration. Children were shown a readymade pipecleaner hook, but were not shown how to make it. This enabled us to discover whether children could bring to mind the means to make the hook for themselves. In comparison to children who had experience of pipecleaner properties, children in both age groups were extremely poor at making the hook tool following the target-tool demonstration if they had not had information regarding pipecleaner properties highlighted for them, i.e. children who did not receive the bending practice. Five-to-six-year-olds who had information regarding pipecleaner properties highlighted were significantly more successful in making the required hook tool following the target-tool demonstration than children who had not had pipecleaner properties highlighted for them. This suggests that if both pieces of information were readily accessible to older children they were able to coordinate it successfully into a solution. Conversely, 4-to-5-year-olds displayed great difficulty in making a hook tool even if they had both pieces of information highlighted for them. This suggests that younger children face a limitation in the domain of tool making in that they are unable to coordinate information even when it is highlighted.

The current findings suggest that children’s main difficulty with tool innovation could be due to problems with retrieving information and recognizing it as a useful solution to the problem. Children were unable to bring to mind additional information when given certain aspects of the task. For example, children who received the bending practice which highlighted the pliable property of pipecleaners were unable to bring to mind information about hooks needed to allow them to innovate the task solution. Similarly, following the target-tool demonstration, children who did not receive the bending practice were unable to bring to mind information regarding the properties of pipecleaners which would enable them to successfully make their straight pipecleaner into a hook tool.

Findings from both age groups fit with the suggestion that tool innovation is an ill-structured problem that requires solvers to both retrieve and coordinate knowledge in order to solve a task. The current studies suggest that 4- to 5-year-olds had difficulty with both of these components. Performance improved with age with 5- and 6- year olds being able to coordinate information in to a useful solution if it had been highlighted, but these older children still displayed great difficulty with bringing to mind this information for themselves. Regardless of how good children's ability to coordinate knowledge is they can never succeed in solving the task if they are unable to retrieve the components of knowledge required and recognize their relevance to the solution. As such, we still see poor innovation ability in this older age group under conditions where the required information is not highlighted for them and they must bring it to mind themselves (Beck et al., 2011; Cutting et al., 2011).

It is surprising that both age groups had difficulty in bringing to mind the required knowledge needed to innovate the solution as previous evidence suggests that children possess all of the individual pieces of knowledge required to solve this tool-innovation task. First, children recognized that a hook was a solution to the task. This is demonstrated in Beck and colleagues' tool selection task (2011, experiment 1) and by children readily manufacturing a hook tool and using it correctly when shown a hook-making demonstration (Beck et al., 2011; Cutting et al., 2011). Second, children have knowledge about the properties of pipecleaners (Beck et al., 2011, experiment 3; Cutting et al., 2011, experiment 1). So if children possess all this information why can they not retrieve it in the context of a tool-innovation task?

Having domain knowledge may not be sufficient to solve ill-structured problems (Jonassen et al., 1993). The children in the current studies are novices. Although these children may possess all the independent pieces of knowledge the task requires, they do not have sufficient experience with the world and the materials to have integrated structural knowledge. We suggest that without this structural knowledge young children lack the flexibility needed to retrieve their knowledge from memory and then coordinate it in order to solve these tool-innovation tasks.

The current study requires children to retrieve and coordinate knowledge regarding the transformation they are required to perform. It seems likely that other types of ill-structured problem, i.e. those missing information from either their start or goal states, would also require the solver to retrieve and coordinate the relevant pieces of information. Future research is needed to test this.

The current findings suggest the main difficulty for both age groups is retrieving knowledge from memory. Younger children in these studies also displayed great difficulty with coordinating their knowledge. As children develop and integrate their knowledge they first improve in their capacity to coordinate information, and can do so readily if all the information needed is highlighted for them. We suggest that as children develop further their knowledge will become more integrated. This will allow them to access and retrieve their knowledge more flexibly, and along with their ability to coordinate knowledge, enable them to solve these ill-structured tool-innovation tasks.

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