PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

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Cite this article: Chappell J, Cutting N, Apperly IA, Beck SR. 2013 The development of tool manufacture in humans: what helps young children make innovative tools? Phil Trans R Soc B 368: 20120409.
http://dx.doi.org/10.1098/rstb.2012.0409

One contribution of 15 to a Theme Issue 'Tool use as adaptation'.

Subject Areas:
behaviour, cognition

Keywords:
tool innovation, comparative cognition, development, physical cognition

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Electronic supplementary material is available at http://dx.doi.org/10.1098/rstb.2012.0409 or via http://rstb.royalsocietypublishing.org.

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The development of tool manufacture in humans: what helps young children make innovative tools?

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We know that even young children are proficient tool users, but until recently, little was known about how they make tools. Here, we will explore the concepts underlying tool making, and the kinds of information and putative cognitive abilities required for children to manufacture novel tools. We will review the evidence for novel tool manufacture from the comparative literature and present a growing body of data from children suggesting that innovation of the solution to a problem by making a tool is a much more challenging task than previously thought. Children's difficulty with these kinds of tasks does not seem to be explained by perseveration with unmodified tools, difficulty with switching to alternative strategies, task pragmatics or issues with permission. Rather, making novel tools (without having seen an example of the required tool within the context of the task) appears to be hard, because it is an example of an 'ill-structured problem'. In this type of ill-structured problem, the starting conditions and end goal are known, but the transformations and/or actions required to get from one to the other are not specified. We will discuss the implications of these findings for understanding the development of problem-solving in humans and other animals.

1. Introduction

For many years, tool use and manufacture were seen as markers of human uniqueness [1,2]. The discovery of not only use, but also manufacture, of tools by a variety of non-human animal species overturned this view (see [3] for a recent and thorough review, and [4]). However, the process of making tools—particularly novel tools—remains somewhat mysterious in both humans and non-humans. For example, while we know that some non-human animals can manufacture tools [3,5–10], the cognitive capabilities required to support this behaviour and the way in which it develops [11–15] are unclear. Even in humans, we know remarkably little about how tool making develops. While we know that children are proficient users of tools [16–20], we know much less about their ability to *make* tools.

If we are to understand the way in which cognition underpins tool making, we need to evaluate the scope of the information about the problem to which tool makers have access. For example, there is an important distinction between manufacture and innovation. When tool makers make a new tool having first seen a suitable example of the tool itself [5,6], or of the tool being used by conspecifics [21,22], they have a template tool-shape to work towards. Assuming that they recognize that the example tool is a suitable tool to solve the task they face (a difficult task in itself, but helped if they have used it themselves or seen others do so), their task is to transform the available materials so that they resemble the example tool. This is a formidable challenge, particularly if modifying the material involves actions that are novel to the individual. We refer to this class of problems as 'tool manufacture'. However, an individual may face a different problem when the situation provides less information about the scope of the task. If the individual faces a task in which they must make a tool to solve it, but they have not seen an example of the required tool (e.g. [7,23]), they must determine for themselves an appropriate tool-shape, and then work out how to transform the available materials into this shape. We refer to this class of problems as 'tool innovation', because the solution—as well as the required transformation—must be invented by the tool user. We will review what is known about tool manufacture and innovation in both human children and non-human species and the conditions influencing their performance. We will also present new data on the possible roles of impulsive behaviour and perseveration on children's performance in tool-innovation tasks. Finally, we will consider whether the insights and techniques gained from experiments on human children can help us investigate tool innovation in non-human species.

2. Review of tool innovation and performance

(a) Tool use, tool manufacture and innovation in human children

One of the pre-requisites for tool manufacture must surely be tool use. The developmental trajectory of tool use in humans has been thoroughly investigated and has revealed that even very young children are adept tool users [17,24,25]. For example, McCarty *et al.* [26] showed that 19 month old toddlers can plan their reach for a spoon so that—once grasped—the spoon is in a comfortable orientation for feeding, with the bowl of the spoon nearest the child's hand. However, this end-state comfort effect occurs only when the tool use is self-directed rather than directed towards another object [27]. Interestingly, this end-state comfort effect has also been observed in lemurs [28] and cotton-top tamarins [29], suggesting that these rudimentary tool-use-related planning abilities either emerged at least 65 Myr ago, or they represent a convergent process in the evolution of motor systems.

Furthermore, even younger infants (9–10 months old) could use a tool to pull an out of reach toy towards themselves, but increasing the spatial gap between the tool and the toy decreased performance significantly [30]. When they are 1–3 years old, their ability to select and use appropriate tools has become much more sophisticated [17]. They can select an appropriate tool to pull an out of reach toy closer, and also transfer their knowledge to perceptually dissimilar but causally equivalent novel tools [17]. Rat-Fischer *et al.* [25] showed that performance on tasks in which the goal is not attached to the tool improved significantly with age between the ages of 14 and 22 months. Again, the spatial gap between the goal and the tool was important, and children found the task progressively harder as this gap increased [25]. While there is still much to be learned about the development of tool-use abilities in children (such as the role of individual differences [31]), our knowledge about the processes involved is quite extensive [31,32].

By contrast, we know much less about children's manufacture and innovation of tools, but we have started to gain some important insights into the processes involved. We know that 3–5 year olds very rarely make a functional tool before demonstration, and even at 7 years old, fewer than half succeed [23]. The majority of children do not succeed without a demonstration of the solution before about 8 years old. However, even the younger children (4 years old) choose a functional over a non-functional tool (in this case, a hook over a straight pipe cleaner), so they appear to understand which tool is required when they choose between pre-made tools and do not have to make one ([23], Experiment 1). Furthermore, as nearly all children succeeded in making a hook once they had received a demonstration, we know that they have sufficient dexterity to make a hook and use it skilfully enough to retrieve the reward. This confirms previous research showing that children are adept tool users [17,25].

(b) What does successful tool innovation require?

Tool innovation is a complex phenomenon, with potential influences from both individual and social learning [33]. For example, innovation involves novel tools, and there are several senses in which the tool made by an individual might be novel. For example, individuals might 'reinvent the wheel' by making a tool that is novel *for them*, make a familiar tool to solve a novel task, or be the first of their population to make a particular tool (see [34,35] for extensive discussion about these distinctions). Once one individual is the first to make a particular tool within a population, their activity can leave direct or indirect information for other individuals and social learning can operate [36]. These other individuals may find examples of the tool, or they may see the innovator making or using it, and thus face a situation in which they can choose an appropriate pre-made tool, or make one to match a template they have seen. Alternatively, other members of the population may not encounter the new tool or see it being made or used, and must therefore invent the tool anew *for themselves*. While social information can make learning how to make tools more efficient, it can potentially retard individual learning by limiting spontaneous exploration [37]. In addition, if individuals imitate a demonstrator's causally irrelevant actions (the so-called 'over-imitation' [38,39]), social information can result in the individual performing less efficient actions than they might through individual learning alone. The social context of tool manufacture and innovation is very important for the spread of novel tools through a population and the development of a material culture [38,40–42], but it is not the main focus of this paper. Instead, we will focus on children's innovation, when they make novel tools without having seen others make or use them, nor having seen relevant pre-made tools. We will separate the problems that children encounter with tool innovation into two main types: those concerning their understanding of the relevant features of the task and those to do with translating that understanding into effective action.

(i) Understanding the relevant features of the task

Many of the problems associated with manufacturing and using tools concern determining the physical properties of the tools, the parameters of the task, and the way in which the two are related (see [17,31]). Non-human animals are also capable of taking into account the geometrical properties such as length and diameter (e.g. New Caledonian crows [43–45]), the weight (e.g. capuchin monkeys [46]), or the rigidity of the tool (e.g. great apes [47], capuchin monkeys [48]), and selecting appropriate tools for the task presented [49]. The physical properties of the materials involved (rigidity, flexibility, geometrical properties, etc.) and how they relate to the parameters of the task may be known through prior experience or exploration. Such exploration may be directed (in the sense that children act to test particular theories, e.g. [50]) or accidental (occurring incidentally in the course of manipulating the materials). We experimentally investigate the influence of exploration of the materials in §4.

Children also need to determine the means by which they could achieve their goal. For example, what shape of tool is needed, and what are the physical constraints and causal relations involved? Information about the physical parameters could be obtained by generalizing from a similar previously experienced situation or by analogy. Children need to determine how the available materials can be transformed to fit the requirements of the task, which may also require some knowledge of materials as explained earlier (e.g. whether the materials can be bent, knotted, re-shaped or parts removed). They also need to decide which actions must be taken to execute the transformation of materials into suitable tools and finally to use the tool to obtain the goal. These competencies comprise the ability to innovate tools.

However, even if children are able to complete all these processes, they may still fail the task because of performance problems that interfere with the appropriate execution of their actions. For example, children may experience mental inflexibility, or problems with executive or inhibitory control. Such problems might lead to performance difficulties that hide children's underlying competence with tools, or alternatively might be an important constraint on the competence itself. Our studies below investigate plausible sources of constraint on children's performance.

(ii) Execution and performance of effective action

It is possible that children may have problems in switching between strategies flexibly [51,52]: success on one kind of task might make it more difficult to adopt the opposite solution in another. This phenomenon (known as 'conservatism') has been demonstrated experimentally in chimpanzees: individuals who had mastered a particular food acquisition technique were reluctant to switch to an alternative—and more efficient—technique [53]. By contrast, Lehner and colleagues [54] found that orangutans readily abandoned preferred techniques when alternative food acquisition methods allowed increased efficiency. Cutting and colleagues ([55], Experiment 1) introduced an unbending task, in which a pipe cleaner that had been folded in half had to be straightened to make a tool long enough to push a pom-pom with a sticker on it from within a horizontal tube. Success was higher on the unbending task than on a hooks task, in which they had to bend a pipe-cleaner into a hook to lift a bucket from a vertical tube (33% of 4–5-year-olds and 56% of 6–7-year-olds succeeded compared to 8% and 30% in hooks task), but there was no effect on success of order of presentation. Thus, success on one task did not hinder (or help) children on the other, and problems switching between strategies do not seem sufficient to explain children's difficulties in succeeding.

There may have been problems with the task pragmatics in Beck and colleagues' experiments [23], because children may not have understood that they had permission to manipulate and transform the materials provided. Alternatively, the prompt from the experimenter that the materials 'can help' to retrieve the sticker might have been interpreted to mean that the materials could be used successfully unmodified. These possibilities were addressed by Cutting and colleagues ([55], Experiment 2). Children in the control condition received an instruction that the materials 'can help' to get the sticker, whereas children in the experimental condition were told that 'you can make something' to get the sticker. There was no difference in success rate between control and experimental conditions [55], suggesting that issues with permissions are not sufficient to explain children's difficulties with this task.

Tool innovation is a multi-step process in which strategies must be selected and executed in the correct order while monitoring success, and it therefore requires inhibitory control to avoid perseveration and impulsivity. Avoiding perseveration is important because children need to be able to switch strategies if the current strategy is unsuccessful. In §3, we test the effect that prompting by the experimenter might have on helping children to recognize that they are persisting with an incorrect strategy.

Impulsivity is another kind of failure of inhibitory control and has a number of different aspects. It can involve the inability to: wait before acting; inhibit behaviours that are inappropriate in the current context or to consider the consequences of actions before understanding the task [56,57]. It is known that children improve substantially in their inhibitory control between the ages of 3 and 5 [51,58], but even adults vary in their impulsivity [56]. Any of these forms of impulsivity might have caused problems for children in our tool-innovation tasks, because they may select and try to use inappropriate distractor materials before they have fully understood the constraints of the task. In addition, they may not have had sufficient opportunity to learn about the properties of the materials, leading them to act impulsively without appreciation of the possibilities. Thus, in §4, we test the involvement of impulsivity and exploration in determining children's success on tool-innovation tasks.

3. The effect of prompting on perseveration

Do children make errors on tool-innovation tasks because they are unable to stop themselves repeating an ineffective action or using an inappropriate material, and are thus unable to switch to a more productive strategy? In a previous experiment [55], we recorded children as perseverating when they inserted an unmodified material into the tube and failed to switch to another material or modify it for the entire duration of the task. Between 8% (1/12) and 32% (7/22) of unsuccessful children showed perseveration, so although it is not an uncommon behaviour and is insufficient to explain the levels of unsuccessful performance we observed [55], avoiding perseveration is a *necessary* step that must be achieved before success. Individuals using only inappropriate or unmodified materials will not succeed in removing the sticker from the tube. Furthermore, it is possible that the children who perseverated in the previous experiment did so because they assumed that the materials they had been given were sufficient to solve the task without modification, or that their actions must be correct because the experimenter did not correct or prompt them.

Thus, in this experiment, we aimed to prevent children from perseverating on an incorrect response by including a 'prompt' condition in which we interrupted them verbally every 10 s in order to suggest that they might do something else. If perseveration interferes with children's ability to solve the task, then those in the 'prompt' condition should perform significantly better than those in the control condition who were not given verbal prompts.

(a) Methods

(i) Participants

The participants were 28 4–5-year-olds (18 boys), mean age 4 years 9 months (4;9), (range 4;4–5;2), and 28 6–7-year-olds

(19 boys), mean age 6;8 (range 6;2–7;2) from a primary school in south Birmingham, UK. The age groups were constructed on the basis of the children's school year groups. In studies on cognitive development, it is usual to group children tested in schools on the basis of how much schooling they have received, and it is the same strategy as used in [23]. The ethnic composition of the sample was 77% Asian, 18% Caucasian and 5% Black.

(ii) Materials

For the hook task, the apparatus consisted of a transparent plastic tube (height 22 cm, width of opening 4 cm) attached vertically to a cardboard base (length 35 cm, width 21 cm), at the bottom of which was a bucket with a wire handle containing a sticker (figure 1). Children were provided with the following materials with which they try to solve the task: three 29 cm pipecleaners (white, black and green) and three 29 cm pieces of string (red, yellow and blue). For the unbending task, the apparatus consisted of a transparent plastic tube (length 22 cm, width of opening 4 cm) attached horizontally to a cardboard base (length 33 cm, width 15 cm), containing a small pompom (diameter 4 cm) with a sticker attached. For the unbending task, children were given three pipecleaners bent in half (unbent length = 22 cm, white, black and green) and three 29 cm pieces of string (red, yellow and blue). Dark blue pipecleaners (lengths 22 cm and 29 cm) were used for the demonstrations. A small clock was used to time the task.

(iii) Procedure

Children were alternately assigned to either the control or the prompt condition based on the teacher's class list. Participants were tested by a female experimenter (NC) in a quiet area just outside the main classroom. The child and experimenter sat facing each other across a table. All children received both the hook and unbending tasks, but remained in the same experimental condition in each task (i.e. control or prompt condition). The order was counterbalanced across participants.

Children were shown the relevant transparent tube, either the vertical tube with the bucket containing a sticker already in place in the bottom or the horizontal tube containing the pom-pom with sticker attached. They were told that if they could get the sticker out they were allowed to keep it. The experimenter then brought out the pieces of string and the pipecleaners (either straight or bent in half) and told the child *'Here are the things you're going to use. Some of them are bendy [bend pipecleaner slightly and straighten] and some of them are wiggly [wiggle string]'*. The experimenter then carried out alternate bendy/wiggly demonstrations with all the materials. The materials were then placed next to the apparatus and the experimenter said *'Can you work out how to get the sticker out?'* The children in the control condition were given 1 min to try to retrieve the sticker (independent phase). Children in the prompt condition were also given 1 min in which to solve the task, but every 10 s the experimenter would interrupt and say *'What else could you do?'* This prompt was not given if children had already initiated the correct solution. If children in either condition had not retrieved the sticker after 1 min, they were encouraged by the experimenter to put down the materials they were using. With the materials remaining on view, the experimenter then said *'look at this'* and using her own dark blue pipecleaner held out a pre-made target tool for the child to view (endstate tool demonstration phase). The children were again encouraged to retrieve the sticker. If, after 30 s, children were still unsuccessful, they were again encouraged to put down the materials they were using. The experimenter then said *'watch this'* and again using her own materials (target tool had been returned to original state), demonstrated the action required to make a functional tool (action tool demonstration phase). The step-wise procedure enabled us to determine whether children unsuccessful at each stage could be helped by providing various forms of demonstration of either the required endstate of the tool, or the action required to transform the tool into the correct shape. As children in both the prompt and control conditions experienced the same step-wise procedure, comparison of the performance between the conditions allowed an evaluation of the effect of prompting on perseveration and performance on the task.

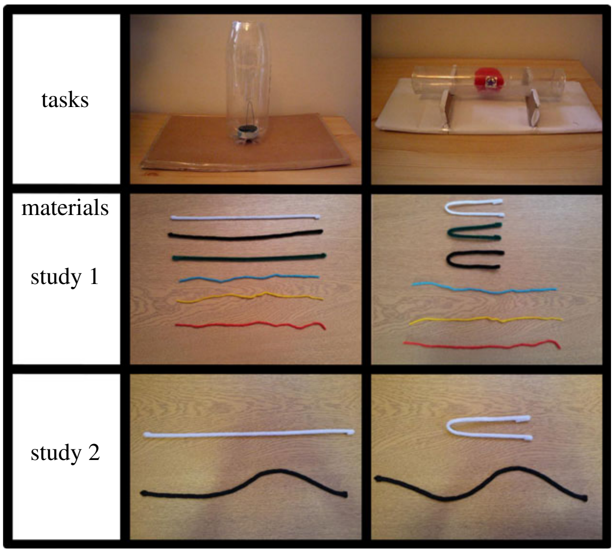

Figure 1. The apparatus and materials used for the hooks task (left column) and unbending task (right column). Note that the ends of the pipecleaners are folded over to prevent children injuring themselves on the wire core. (Online version in colour.)

Pipecleaners that differed in colour from those used in the main task were used in the demonstrations to avoid the need for counterbalancing. Children in the prompt condition continued to receive prompts every 10 s throughout the demonstration phases.

In both experiments, we used χ^2-tests to analyse the success rate and level of perseveration where the sample size was sufficiently large, and Fisher's exact test (FET) where the sample size was too small to permit use of χ^2-tests. Raw data for both experiments are provided in the supplementary material. There were no significant differences in success due to gender (FET, $p > 0.464$ in all cases), so the data were collapsed across gender for the remaining analyses.

(b) Results and discussion

(i) Effect of prompt condition on success

Prompting children to ask what else they could do did not improve success on the task for either age group on either the hook or the unbending tasks (figure 2). There was no significant difference in levels of success either before any demonstration, when children had to solve the task independently (independent phase) (hook: 4–5 year olds, FET, $p = 0.203$; 6–7 year olds, $\chi^2_{(\text{d.f.}=1,n=28)} = 0.223$, $p = 0.637$; unbending: 4–5 year olds, FET, $p = 0.420$; 6–7 year olds, $\chi^2_{(\text{d.f.}=1,n=28)} = 0.144$, $p = 0.705$; see independent phase bars in figure 2), or following the endstate

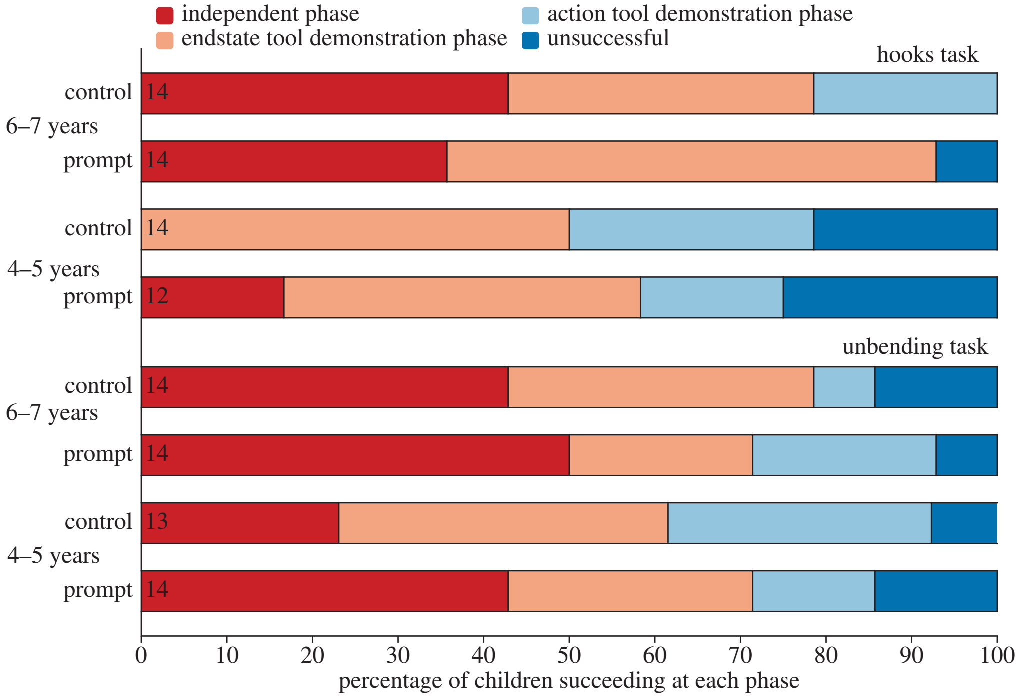

Figure 2. Perseveration experiment. Percentage of children succeeding at each successive phase of the experiment, and the percentage who were unsuccessful, in each of the age groups and in both the prompt and control conditions. Independent phase = before any tool demonstrations were provided; endstate tool demonstration phase = after children had been shown the required tool endstate; action tool demonstration phase = after a demonstration of the required action to transform the pipecleaner had been provided. Numbers at the base of each bar indicate the number of children in each group. (Online version in colour.)

tool demonstration (hook: 4–5 year olds, $\chi^2_{(\mathrm{d.f.}=1,n=24)} = 0.000$, $p > 0.999$; 6–7 year olds, FET, $p = 0.200$; unbending: 4–5 year olds, FET, $p > 0.999$; 6–7 year olds, FET, $p > 0.999$; see endstate tool demonstration phase bars in figure 2). The effect of condition on success after the action tool demonstration could be computed only for the 4–5 year olds for the hook task because of a small sample size in the older group, but there was no significant difference in success between the prompt and control groups for either of the tasks (hook: FET, $p > 0.999$; unbending, 4–5 year olds, FET, $p = 0.524$; 6–7 year olds, FET, $p = 0.486$; see action tool demonstration phase bars in figure 2).

However, children in the prompt and control conditions did differ in the number of times they inserted material into the tube. After successful children had been excluded from the data (number of children excluded: hooks task = 14; unbending task = 22), the number of insertions of materials (which could be the same material inserted again after removal, or a different material) was coded. Children in the prompt condition made significantly more insertions than those in the control condition ($t_{39} = 2.050$, $p = 0.047$) in the hook task, but not in the unbending task ($t_{31} = 0.813$, $p = 0.423$). There was no significant difference between conditions in either task for the number of children who changed the material they inserted into the tube.

(ii) Perseveration

Perseveration was recorded when a child inserted a material (unmodified) into a tube and then persisted with that material for the entire duration of the task (1 min). In the unbending task, only two children perseverated, both in the 4–5 year old group (one was in the prompt and one in the control condition). In the hook task, six children (4–5 year olds) perseverated. After excluding children who succeeded in obtaining the sticker (number of children excluded: prompt condition = 2; control condition = 5), there was a significant difference in the number of perseverators between the two conditions (FET, $p = 0.024$), with all of the perseverating children in the control condition.

(iii) Task order

Children in the 4–5 year old group were more likely to succeed on the unbending task before demonstration if they received this task first (6 versus 3, FET, $p = 0.046$). There were no other effects of task order for the other task or for the other stages of testing.

These results support our previous finding that perseveration is not sufficient to explain the difficulties that children have with tool innovation [55]. If they persisted with one material under the mistaken impression that the experimenter had given them functional tools, or that their actions must be correct because the experimenter had not intervened verbally, the frequent prompts asking what else they could do should have acted as a cue to change strategy. If so, children in the prompt condition should have shown more success compared to the control condition. We know that our prompt condition functioned in the way we intended because while perseveration was low overall, significantly fewer 4–5 year old children in the prompt condition in the hook task perseverated compared to those in the control condition. Furthermore, the fact that children in the prompt condition also made significantly more insertions of material into the tube in the hook task (though not the unbending task), suggests that the prompts may have cued them to be more active. Clearly, while the prompts may help children to recognize that they need to try something else, they do not help them reveal their understanding of the solution to the task. Conversely, children in the prompt condition did not do worse on the task compared with the control condition, so the frequent interruptions also did not seem to cause them undue confusion.

4. Impulsivity and exploration: the effect of a delay

In §3 and [55], we have shown that children's inability to stop implementing an unsuccessful strategy does not seem to explain their difficulty with innovation tasks. In this experiment, we test a broader aspect of impulsivity: the tendency to act without considering the consequences.

We have observed in previous experiments that children tend to pick up materials and start to act very quickly after the onset of the experiment. They may do this because their attention is drawn by irrelevant stimuli [57] or because they are in the grip of naive theories, resulting in inappropriate responses. For example, Karmiloff-Smith & Inhelder [59] tested children's ability to balance unevenly weighted rods on a pivot. Four-year-old children succeeded in completing the task through a trial-and-error strategy, but 6 year olds had a naive theory that the rods should balance in the middle and were unable to abandon this strategy to balance the rods at their centre of mass. By contrast, 8 year olds held a similar theory, but they were able use evidence from their own failed attempts to overcome the theory and adapt their actions appropriately [59].

All children in the tool-innovation experiments seem to understand the need to insert material into the tube and make contact with the bucket. We know that an awareness of the importance of contact in causal events appears very early and has been demonstrated in children from 6 months old [60,61]. It is possible that this early naive theory about contact overwhelms children's ability to think about the problem in more diverse ways and discover the need for *connection* in addition to contact.

Recent studies have shown that inhibitory problems in cognitive tasks can be reduced, and performance improved, by the introduction of a delay before children are allowed to respond. In Diamond *et al.*'s study [62] children performed a simple Stroop-type task. When they saw a picture of the Sun they had to say 'night' and when they saw the Moon they had to say 'day'. Four year olds find this difficult and are as likely to give the incorrect as correct response. However, when a delay of just a few seconds was introduced in between showing children the card and their response, performance improved significantly. Beck *et al.* [63] showed that similar improvement was seen on a counterfactual reasoning task when a delay was introduced. Three and four year olds in this task heard a short story in which an object moved from one location to another. When asked counterfactual questions 'What if the object had not moved where would it be?' children at this age tend to answer incorrectly with the current situation, a difficulty that has been attributed to inhibition (see [64]). When there was a delay between asking the question and the child's answer the number of correct answers increased.

In order to determine whether impulsive responding was responsible for the problems that children have with making novel tools, we designed an experiment in which one group of children was given an opportunity to explore the materials to be used as tools before they were allowed to interact with the apparatus, imposing a delay. The opportunity to explore the materials in the delay also ensured that children had manipulated the materials and were familiar with their properties: something they may not have taken sufficient time to do in previous experiments. While the warm-up activities in our previous experiments [23,55] gave them experience of manipulating materials, there is evidence that children learn more about materials when they explore them for themselves rather than being shown them in a pedagogical context [37].

By enforcing a delay before action can be taken impulsive behaviours should be reduced. Thus if impulsive actions are inhibiting success, children in the delay/explore condition should perform better than those in the control condition.

(a) Methods

(i) Participants

The participants consisted of 29 4–5 year olds (13 boys), mean age 4 years 8 months (4;8), (range 4;3 to 5;2), and 24 6–7 year olds (11 boys), mean age 6;9 (range 6;3 to 7;2) from a primary school in south Birmingham, UK. The ethnic composition of the sample was 91% Caucasian, 6% Black and 3% other/unknown.

(ii) Materials

The basic apparatus used for both the hook and unbending tasks was identical to that used for the perseveration experiment; however, the materials provided differed (figure 1). For the hook task, children were provided with a pipecleaner (length 29 cm) and a piece of string (length 29 cm). For the unbending task, they were given a pipecleaner bent in half (unbent length 22 cm) and a piece of string (length 29 cm). A small clock was used to time the task.

(iii) Procedure

Children were alternately assigned to either the control condition or to the experimental (delay/explore) condition. All children received both tasks in the same session on the same day. The order was counterbalanced across participants.

Children were shown the relevant transparent tube and told that if they could get the sticker out they were allowed to keep it. The experimenter then brought out the string and pipecleaner (either straight or bent in half) and told the child *'Here are the things you're going to use. This one's bendy [bend pipecleaner slightly and straighten] and this one's wiggly [wiggle string]'*. The materials were placed on the base of the apparatus, which was out of the child's reach. In the control condition, the apparatus was then placed in front of the child and the experimenter said *'Can you work out how to get the sticker out?'* In the delay/explore condition after the demonstrated materials were placed on the base of the apparatus, the experimenter brought out identical new materials and said *'These are just the same as the ones you are going to use. But before you try to get the sticker for real, you can play with these and try to work out how you will get the sticker out'*. Children were given 10 s to explore the materials. The materials were then taken away and the apparatus and original materials were placed in front of the child and the experimenter said *'OK, can you get the sticker out?'* Children in both conditions were given 1 min to try to retrieve the sticker (independent phase). 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*

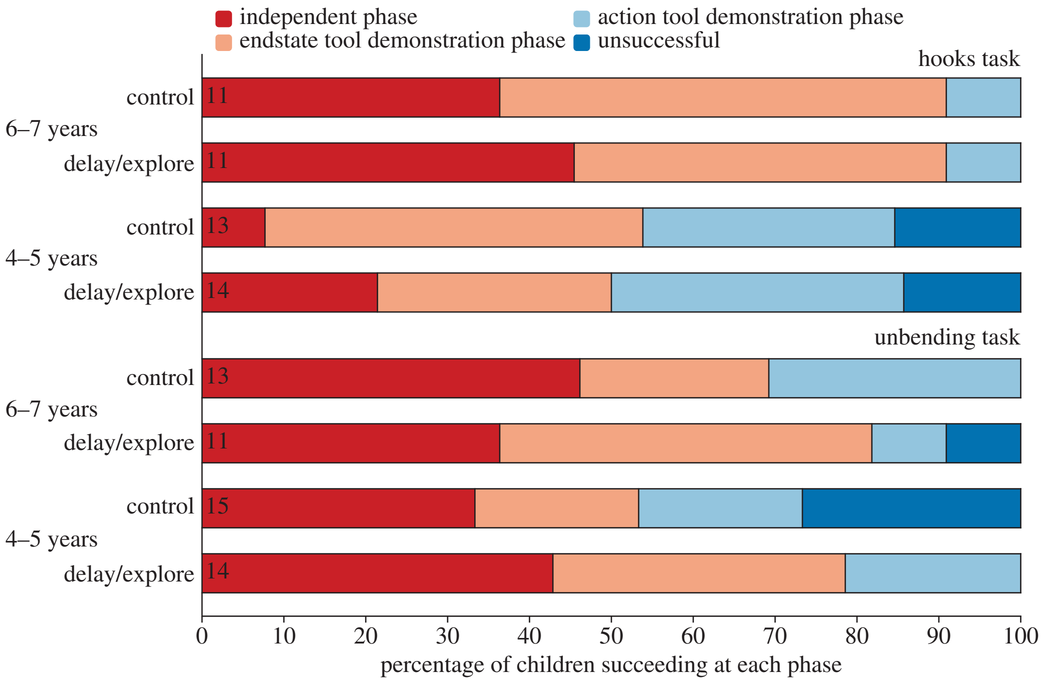

Figure 3. Impulsivity experiment. Percentage of children succeeding at each successive phase of the experiment, and the percentage who were unsuccessful, in each of the age groups and in both the delay/explore and control conditions. Independent phase = before any tool demonstrations were provided; endstate tool demonstration phase = after children had been shown the required tool endstate; action tool demonstration phase = after a demonstration of the required action to transform the pipecleaner had been provided. Numbers at the base of each bar indicate the number of children in each group. (Online version in colour.)

Table 1. Impulsivity experiment. Number of children in the delay/explore condition categorized as showing each of the tool-related exploratory behaviours during the 10 s exploratory delay. As the delay was very short, each child only performed one of the behaviours listed.

age group	*n*	touch	pick up	combine	bend (non-target tool)	bend/unbend target tool
		hook task				
4–5	14	2	8	2	1	1
6–7	11	1	2	1	4	3
		unbending task				
4–5	14	2	7	1	2	2
6–7	11	2	3	4	0	2

to get the sticker out?' and '*Maybe you could use these things to help you*'. If, after 1 min, the child had not retrieved the sticker, they were encouraged to put down the materials they were using. The experimenter then gave the child an endstate tool demonstration with her own pipecleaner followed by the action tool demonstration if required as in the Perseveration experiment (see §3). There were no significant differences in success due to gender (FET, $p > 0.123$ in all cases), so the data were collapsed across gender for the remaining analyses.

(b) Results and discussion

Table 1 shows the behaviours carried out by children during the delay/explore period. The younger children had a tendency to just pick up the materials and explored them very little. Older children showed more exploratory behaviours such as combining and bending. These descriptive data show that children engaged with the materials in the delay/explore condition, so their experience differed from children in the control condition. Condition had no effect on children's first choice of material in the main innovation task. All except three children chose the pipecleaner first in the hook task, all children that chose the string were in the control condition but there was no difference between conditions (FET, $p = 0.238$). Nine children in total chose the string first in the unbending task, four in the delay/explore group and five in the control group, again demonstrating no difference between the two conditions (FET, $p > 0.999$).

(i) Effect of delay/explore condition on success

For the hook task, there was no difference in success levels before any tool demonstration between the delay/explore and control conditions ($\chi^2_{(\mathrm{d.f.}=1,n=49)} = 0.783$, $p = 0.376$; see independent phase bars in figure 3). This finding was seen in both age groups (4–5 year olds, FET, $p = 0.596$; 6–7 year olds, FET, $p > 0.999$). There was also no difference in success levels during the independent phase between the two conditions for the unbending task ($\chi^2_{(\mathrm{d.f.}=1,n=53)} = 0.305$, $p = 0.581$). Again this finding was the same across both age groups (4–5 year olds, FET, $p > 0.999$; 6–7 year olds, FET, $p > 0.697$).

Comparing the performance of children in the delay/explore condition with those in the control condition, it is clear that condition made no difference to success following the endstate tool demonstration for either age group on both tasks (hook task: 4–5 year olds, FET, $p = 0.680$; 6–7 year olds, FET, $p > 0.999$; unbending task: 4–5 year olds, FET, $p = 0.650$; 6–7 year olds, FET, $p = 0.592$; see endstate tool demonstration phase bars in figure 3). Ignoring the experimental condition, for the hook task, the 6–7 year olds were more successful following the endstate tool demonstration than were the younger 4–5 year olds ($\chi^2_{(\mathrm{d.f.}=1,n=36)} = 5.783$, $p = 0.016$). No difference between the age groups was seen following the endstate tool demonstration for the unbending task ($\chi^2_{(\mathrm{d.f.}=1,n=34)} = 0.971$, $p = 0.324$).

Comparing the performance of children in the delay/explore condition with those in the control condition, it is clear that condition also made no difference to success following the action tool demonstration for the 4–5 year olds for either task (both tasks FET, $p > 0.999$; see action tool demonstration phase bars in figure 3). No comparisons could be made for the 6–7 year olds as all children in both conditions were successful following the action demonstration. There was also no difference in success between the two age groups on both tasks (hook task, FET, $p > 0.999$; unbending task, FET, $p = 0.054$).

Together these results indicate that the delay (and the resulting opportunity to explore the materials) did not help children succeed on either of the tool-innovation tasks. Thus, it appears that neither impulsive behaviour nor failure to explore the materials adequately was sufficient to explain children's difficulty with these tasks.

5. Conclusion

In §§3 and 4, we have shown that children's striking lack of success in these tool-innovation tasks is not explained by impulsive behaviour, a lack of opportunity to explore materials or by perseveration. Because even 4-year-old children are able to choose the correct pre-made tool when given a choice [23], and can make a suitable tool successfully when given a demonstration of the required transformation ([23,55] and above), why does the tool-innovation task present such difficulties for children?

One strategy to address this problem should be to develop different tasks, drawing on the non-human animal literature [48,65,66], to investigate whether tool innovation is difficult across different types of transformation and materials. For example, does tool innovation follow the type of hierarchy suggested by Kacelnik *et al.* [67]? However, early data on this [68] and the finding that children find it difficult to make straight tools as well as hooks [55] suggest tool-innovation difficulties are unlikely to be restricted to a very narrow set of tasks. What is more, recent evidence that children's innovation in rather different physical causality tasks that use water as a tool show similar developmental trajectories [69,70] suggests that while expanding the range of tasks will no doubt be informative, there seems to be a genuine problem with innovation in physical cognition tasks for young children.

We propose that this task is inherently difficult, because it is an example of an ill-structured task [55,71]. Ill-structured tasks are those in which the problem itself does not directly provide a solution, requiring the subject to generate one. In the standard versions of our tool-innovation tasks, children have clear initial conditions (the sticker is in the tube, and they are provided with materials) and a clear goal (get the sticker out of the tube). However, none of the necessary intervening steps between the initial conditions and the goal are specified, and appropriate strategies must be generated by the subject. Executive function tasks have been designed that specifically probe ill-structured tasks [72]. Performance on these tasks and standard well-structured executive tasks can be dissociated experimentally [71], suggesting that they may depend on somewhat different cognitive abilities. An important next step for the literature is to try to define more precisely the kinds of information that might increase children's success on our ill-structured tool-innovation task. Seeing the transformation required (that is, watching the experimenter bend the pipecleaner into a hook) clearly improves performance [23,55], but the kinds of information that help children to bridge the gap between the starting conditions and the desired goal need to be analysed.

There are several reasons why it is important to understand the development of tool innovation in humans. Tool innovation has performed a vital role in the evolution of our own species, and by studying children whose ability to innovate is still developing, we can gain insights into the psychological processes supporting it. This has important implications for understanding these processes in humans, but also means that our baseline assumptions about what constitutes 'human-level performance' in non-human animals may not be accurate [39,73,74].

In addition, it may be helpful to translate some of the experimental techniques and ways of thinking about the structure of the problem faced by subjects back into experiments on non-human animals. For example, viewing tool-innovation tasks in non-humans as ill-structured tasks helps us to distinguish between the demands of performing a given task and the competence to solve it in principle, and highlights the need to define more clearly the processes required for the subject to be able to 'fill in the gaps' between the starting conditions and the goal. It suggests that tool knowledge—whether it comes from culture or individual learning—not only equips an individual with a stock of solutions to a problem they may encounter, but may also be a critical source of analogies that individuals must impose for themselves in the solution of novel, ill-structured problems. It also raises questions about whether other behaviours might also count as ill-structured tasks. For example, in nest-building behaviours, the animal starts with unordered materials (such as sticks or blades of grass) and a defined goal (a particular shape of nest), but if it has never observed the construction of a nest, it may have to generate the necessary intervening transformations itself [75].

Interdisciplinary research can be extremely enlightening: experiments with human children originally inspired by those on New Caledonian crows [5] have in turn generated new approaches and insights that might be fruitfully applied to research on non-human animals, shedding further light on the cognitive basis of innovation and its role in culture.

Acknowledgements. We thank the teachers and children at The Meadows and King David primary schools for their help and participation. We also thank two anonymous reviewers and the editor for their helpful comments on the manuscript.

Funding statement. This research was funded by ESRC (grant no. ES/J023485/1).

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