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Learning Versus Reasoning To Use Tools In Children

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Abstract

Tool behavior might be based on two strategies associated with specific cognitive mechanisms: Cued-learning and technical-reasoning strategies. We aimed to explore whether these strategies coexist in young children and whether they are manifest differently through development. We presented 216 3- to 9-year-olds with a vertical maze task, consisting in moving a ball from the top to the bottom of a maze. Two tool-use/mechanical actions were possible (rotating action or sliding action). Three conditions were tested, each focused on a different strategy. In the Opaque-Cue condition (cued-learning strategy), children could not see the mechanical action of each tool. Nevertheless, a cue was provided according to the tool needed to solve the problem. In the Transparent-No-Cue condition (technical-reasoning strategy), no cue was presented. However, children could see the mechanical actions associated with each tool. In the Transparent-Cue condition (cued-learning and/or technical-reasoning strategy) children saw both the mechanical actions and the cues. Results indicated that the Opaque-Cue and Transparent-Cue conditions were easier than the Transparent-No-Cue condition in all children. These findings stress that children can use either cued learning or technical reasoning to use tools, according to the available information. The behavioral pattern observed in the Transparent-Cue condition suggests that children might be inclined to use technical reasoning, even when the task can be solved through cued learning.

Keywords:

Tool Use; Cued Learning; Technical Reasoning; Childhood; Cognitive Strategies.

Introduction

Tool behavior is rare in nonhuman animals, with few species exhibiting this behavior (Hunt, Gray, & Taylor, 2013; Shumaker, Walkup, & Beck, 2011). Yet, it is widespread in humans. An outstanding question is to understand the underlying cognitive bases. Tool behavior might be based on at least two kinds of cognitive skills: Cued learning and causal reasoning (hereafter called technical reasoning; Osiurak, Jarry, & Le Gall, 2010; Osiurak, Lesourd, Navarro, & Reynaud, 2020; for a similar view, see Penn, Holyoak, & Povinelli, 2008; Penn & Povinelli, 2007; Vaesen, 2012; Wolpert, 2003). Cued learning corresponds to the ability to learn arbitrary contingencies between an action and its effect on the basis of spatial-relational information. An individual can learn that pressing the red button, not the blue button, is the appropriate action to switch on the TV. In this case, the contingency is arbitrary because the alternative action could have been appropriate (i.e., pressing the blue button) but is inappropriate because of, for instance, social conventions. By contrast, technical reasoning is the ability to reason about objects (including tools) on the basis of representations of physical properties (e.g., weight, solidity). In this case, the abstract nature of these representations allows the individual to make analogies between different situations and, as a result, to transfer what is understood in one situation to another (i.e., transfer; see also Carey, 1985; Mandler, 2004; Seed & Call, 2014). An individual can use appropriately a lemon squeezer equipped with a lever arm because they understand (at least implicitly) that lowering the arm generates a lever action on the squeezer, which in turn generates a squeezing action on the lemon.

The question of whether nonhuman – notably tool-using – species possess technical-reasoning skills has been at the heart of research on animal tool use. Evidence indicates limitations on the ability of nonhuman animals (including tool-using species) to deal with tool-use situations (Gruber, 2016; Povinelli, 2000; Povinelli & Frey, 2016; Visalberghi & Limongelli, 1994) or to show transfer (Martin-Ordas, Call, & Colmenares, 2008; O'Neill, Picaud, Maehner, Gahr, & von Bayern, 2019). This suggests that animal tool use might not be based on technical reasoning. However, other findings have questioned this hypothesis (Hermann, Wobber, & Call, 2008), notably because signs of transfer in tool-use situations have been observed in some nonhuman animals (Martin-Ordas, Jaek, & Call, 2012; van Horik & Emery, 2016). In other words, the question of whether at least some nonhuman species possess technical-reasoning skills is still a matter of debate.

In humans, neuropsychological evidence has demonstrated that, in adults, tool use is supported by technical-reasoning skills. For instance, studies of left brain-damaged patients have reported a strong link between the ability to use everyday tools and the ability to solve mechanical problems using/making novel tools on the basis of their physical properties (Goldenberg & Hagmann, 1998b; Hartmann, Goldenberg, Daumüller, & Hermsdörfer, 2005; Jarry et al., 2013; Osiurak, Jarry, Lesourd, Baumard, & Le Gall, 2013; Osiurak et al., 2009). In addition, tool-use disorders are associated with damage to the left inferior parietal cortex, and particularly the area PF (Goldenberg & Spatt, 2009; Martin et al., 2016; Salazar-Lopez, Schwaiger, & Hermsdörfer, 2016), a finding corroborated from neuroimaging data (Reynaud, Lesourd, Navarro, & Osiurak, 2016; Reynaud, Navarro, Lesourd, & Osiurak, 2019). It has also been shown that left brain-damaged patients with tool-use disorders can learn how to use physical tools after several weeks of training. Nevertheless, there is no generalization of training effects from trained to non-trained tool-use activities (i.e., no transfer; Goldenberg, Daumüller, & Hagmann, 2001; Goldenberg & Hagmann, 1998a). In broad terms, left inferior parietal lobe lesions impair the ability to use tools through technical reasoning, but not cued learning. This last finding is of interest because it illustrates that humans (at least adults) might have two strategies to use tools: A cued-learning strategy and a technical-reasoning strategy.

Given that adults appear to follow either strategy to use tools, the next question is whether these strategies coexist in children at an early age and whether they are manifest differently through development. In recent years, particular interest has been paid to the development of tool-innovation skills in children. Tool innovation requires the making of a novel tool that is designed by the individual without previously witnessing a demonstration of how to do so (i.e., without social learning). The hook-bending paradigm has been used to explore this aspect (Beck, Apperly, Chappell, Guthrie, & Cutting, 2011; see also Weir Chappell, & Kacelnik, 2002). In this paradigm, a bucket containing a target is placed at the bottom of a vertical tube, which is too narrow to reach into using a hand. Children are presented with a straight pipecleaner. The solution (i.e., tool innovation) is to bend the pipecleaner to make a hook, which can be used to retrieve the bucket. Evidence indicates that children perform remarkably poorly on this task until 8 years of age (Beck et al., 2011; Chappell, Cutting, Apperly, & Beck, 2013; Cutting, Apperly, & Beck, 2011; Cutting, Apperly, Chappell, & Beck, 2014; see also Remigereau et al., 2016). In this paradigm, children cannot learn any contingency between their action and the effect because of the presentation of a single trial. Thus, solving this task could require technical-reasoning strategies and not cued-learning strategies, thereby suggesting that technical-reasoning skills might continue to grow until 8 years of age. Neldner, Mushin, and Nielsen (2017) introduced a subtle modification to this paradigm, in presenting children with a pipecleaner that was bent into one end to form a hook and with its other end rounded over into a loop. Thus, the pipecleaner was too short and wide to retrieve the target. Children had nevertheless to innovate in unbending the looped end to produce an appropriate tool. They found that 45% of 3- to 5-year-olds were able to find out the solution in this configuration compared to typical rates of about 10% in other studies (Beck et al., 2011; Cutting et al., 2011, 2014). A potential interpretation is that this configuration helped the children to use an alternative strategy based on cued learning. However, as explained above, the presentation of a single trial makes this interpretation unlikely. Another interpretation is that technical-reasoning skills can be efficient relatively early in childhood but are mediated by the capacity to construct hierarchical relations among the tool, task, and goal during tool making. Support for this interpretation comes from a recent study in 3- to 6-year-olds, which showed that success in the hook-bending paradigm is predicted by the performance in a hierarchical structuring task (Gönül, Takmaz, Hohenberger, & Corballis, 2018).

Another study of interest is the work of Seed and Call (2014), who explored more directly the use of either strategy in a physical problem-solving task. The task was to retrieve a ball by rolling it away from a barrier or a trap using their fingers (Experiments 1, 3 and 4). In some configurations, the presence of a shelf was required to retrieve the ball, whereas in others its presence led to a trap. In the transparent condition, children could see the different parts of the problem (i.e., gap where a shelf could be fitted, barrier, trap), which suggests that they could use technical-reasoning strategies to solve this condition. In the opaque condition, the front face of the problem was covered with cardboard and Velcro markers were stuck in the locations corresponding to the relevant parts of the problem (i.e., shelf, barrier, trap). Thus, these cues could also predict the right answer as in the transparent condition, although cued-learning strategies were required to solve it. The results indicated that half of the 2.5-year-olds and all of the 3.5-

year-olds, but not the 2-year-olds, were able to solve the transparent condition. By contrast, most of the 2.5- and 3.5-year-olds failed to solve the opaque condition. Some 5.5- and 6.5-year-olds were able to solve it. Thus, this finding indicates that children could use technical-reasoning strategies earlier than cued-learning strategies, which is partly inconsistent with the aforementioned literature on tool innovation.

To sum up, an unresolved question is whether cued-learning and technical-reasoning strategies coexist in children at an early age and whether they are manifest differently through development. The goal of this study was to contribute to answering this question. To do so, we presented 216 3- to 9-year-olds with a vertical maze task, in which children had to direct a ball from the top to the bottom of a maze without sending it to an incorrect side exit (**Fig. 1**). There was one choice point in each maze (trial) at which two tool-use/mechanical actions were possible (i.e., a rotating action or a sliding action). For half of the trials, the rotating action was the correct action and the sliding action the incorrect action, and vice versa for the other half of the trials. There were three conditions. In the Opaque-Cue condition, children could choose between the two tools, but they could not see the mechanical actions associated with them (**Fig. 1**). A cue was nevertheless presented, systematically associated with the necessary tool. This cue corresponded to a picture depicting the mechanical action generated by the tool (i.e., a picture of a "rotating" arrow or of a "sliding" arrow; **Fig. 1**). Therefore, the only way to solve this condition (i.e., to achieve above-chance performance) to was to use a cued-learning strategy that linked the cue to the correct tool-use action. In the Transparent-No-Cue condition, no cue was presented. However, children could see the mechanics associated with each tool (**Fig. 1**). Given that the choice of the correct tool/mechanical action required understanding its effect on the motion of the ball, a technical-reasoning strategy was needed here to achieve above-chance performance, as in the transparent condition in the study of Seed and Call (2014). Nevertheless, it could be suggested that this condition could also be solved through cued learning. Indeed, the individual, for instance, learning to link the use of one of the two tools with specific details of the maze (e.g., the location and orientation of some slopes, which differed according to the maze; **Fig. 1**). However, the study of Seed and Call (2014) indicated that such learning based on specific details is very difficult for children, even when the important details of the problem are made salient with Velcro markers. Finally, we added a third condition, namely, the Transparent-Cue condition, in which the children could see both the physics of the maze and the cues. As a result, both strategies could be used to solve this condition (i.e., to achieve above-chance performance). Our investigation focused on children between the ages of 3 and 9 years based on aforementioned findings, which indicate discrepancies notably in the development of both strategies within this age range.

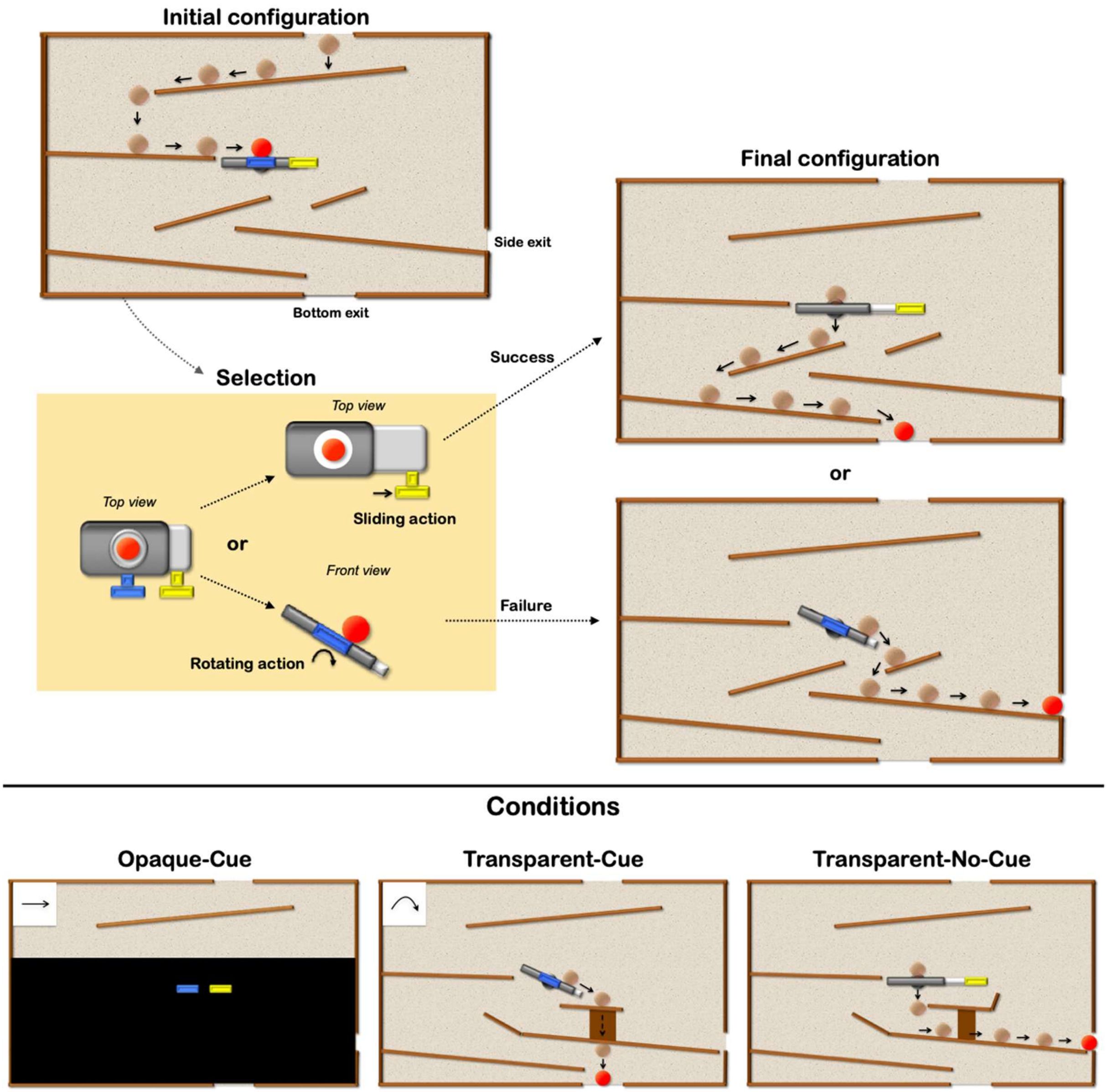

Fig. 1. The vertical maze task. As shown in the upper panel, the task was to move a ball from the top to the bottom of a maze. The ball was introduced by the experimenter into the maze and moved from the top of the maze to a platform where it stopped (Initial configuration). The children had to choose (Selection) between using a blue tool (rotating action) or a yellow tool (sliding action). As illustrated in the upper panel (Maze A), in half of the trials, the correct response was to use the yellow tool, allowing the ball to move to the bottom of the maze (Final configuration; Success). In this configuration, the incorrect response was to use the blue tool, moving the ball to the right exit (Failure). In the other half of the trials, the blue tool was the correct response (i.e., Maze B shown in the lower panel). The three experimental conditions are shown in the lower panel. The cue for the sliding action (Yellow tool) and the cue of the rotating action (Blue tool) are also shown in the Opaque-Cue and Transparent-Cue conditions, respectively.

Methods

Participants

The sample consisted of 216 children from mixed socioeconomic backgrounds and ethnicities (108 girls and 108 boys; M_{Age} = 6.21 years; SD_{Age} = 1.74; Range: 3.21–9.23). The children were recruited and tested at 10 kindergarten and primary schools in France. Our experiment consisted of three conditions. We aimed to have relatively similar age distributions for the three conditions, with a constant proportion of children for each age (i.e., from the age of 3 to 9 years). We also controlled for the potential effect of gender. Therefore, the children were recruited based on their kindergartner/school class and their gender (**Table 1**). An informed consent form was signed and returned by each child's parent or legal guardian. The study was approved by the local ethics committee and conducted in accordance with the Declaration of Helsinki.

Materials and Procedure

The children were instructed to move a ball from the top to the bottom (i.e., success) of a vertical maze of 30-cm height, 50-cm length and 5-cm width (**Fig. 1**), without moving it to the side exit (i.e., failure). Once introduced in the maze, the ball rolled down two ramps before stopping at a platform. At this step, there were two possible mechanical actions: Rotating or sliding (**Fig. 1**). There was only one choice point in each version of the maze. Two mazes were built, one (i.e., Maze A) for which the sliding action was correct (bottom exit) and the rotating action incorrect (side exit), and vice versa for the other (Maze B). The rotating and sliding actions could each be performed using a different tool (a blue one and a yellow one, respectively) pre-inserted at different positions of the platform. The tools were pre-inserted because insertion needed very fine motor actions, which could have prevented some young children from performing the task because of limited dexterity (see Seed & Call, 2014 for discussion on this aspect). The children were asked to use one of the two pre-inserted tools at this choice point to move the ball to the bottom of the maze.

Table 1.
Age distribution in the Opaque-Cue, Transparent-No-Cue, and Transparent-Cue conditions.

	Age group*	Min	Max	Mean	SD	N_{Male}	N_{Female}
Opaque-Cue	3-4	3.21	4.19	3.82	0.43	6	6
	4-5	4.26	5.19	4.52	0.33	6	6
	5-6	5.04	6.13	5.52	0.38	6	6
	6-7	6.26	7.24	6.52	0.34	6	6
	7-8	7.79	8.08	7.89	0.08	6	6
	8-9	8.56	9.20	8.79	0.24	6	6
Transparent-No-Cue	3-4	3.29	4.18	3.71	0.31	6	6
	4-5	4.26	5.16	4.86	0.34	6	6
	5-6	5.24	6.08	5.75	0.27	6	6
	6-7	6.43	7.17	6.95	0.19	6	6
	7-8	7.26	8.17	7.95	0.34	6	6
	8-9	8.30	8.74	8.48	0.14	6	6
Transparent-Cue	3-4	3.49	3.78	3.61	0.10	6	6
	4-5	4.59	5.00	4.83	0.14	6	6
	5-6	5.43	5.66	5.54	0.08	6	6
	6-7	6.63	7.01	6.76	0.13	6	6
	7-8	7.40	7.77	7.59	0.12	6	6
	8-9	8.30	9.23	8.75	0.26	6	6
Opaque-Cue	All	3.21	9.20	6.17	1.80	36	36
Transparent-No-Cue	All	3.29	8.74	6.28	1.72	36	36
Transparent-Cue	All	3.49	9.23	6.18	1.74	36	36

*Age group: 3-4, first year of kindergartner; 4-5, second year of kindergartner; 5-6, third year of kindergartner; 6-7, first year of primary school; 7-8, second year of primary school; 8-9, third year of primary school. SD, standard deviation.

Before beginning the task, the maze was presented without the ball, and children had to perform each mechanical action twice by themselves to show competence (Yellow tool/Sliding action: "Please can you grasp the yellow tool and slide it to the right"/"Peux-tu saisir l'outil jaune et le faire glisser vers la droite" [in French]; Blue tool/rotating action: "Please can you grasp the blue tool and turn it"/"Peux-tu saisir l'outil bleu et le faire tourner" [in French]). If needed, the experimenter helped the children perform the correct mechanical action and asked them to perform it again on their own. In the Transparent-No-Cue condition, there was no cue, but the children could directly observe the mechanics between the tools and the platform. In the Transparent-Cue condition, an additional cue with the symbol of the correct action to perform was presented in the top left corner of the maze. In the Opaque-Cue condition, a cue was also presented, but there was a black mask hiding the lower part of the maze, preventing the children from seeing the platform and, therefore, the mechanical actions associated with the two tools. For the Transparent-Cue and Opaque-Cue conditions, the experimenter mentioned that the cues (**Fig. 1**) could be helpful to select the appropriate tool ("Do you see this drawing? It is useful to know which of the two tools allows you to move the ball to the bottom of the box"/"Est-ce que tu vois ce dessin? Il sert à savoir lequel des deux outils permet de faire avancer la balle vers le bas de la boîte" [in French]). However, the experimenter did not name the cue, nor did she manipulate the tools in her hands. In other words, the cue was not associated with a gesture performed by the experimenter. The children were randomly assigned to the three conditions (i.e., between-subject factor; n = 12 for each condition/age group; **Table 1**). Each child completed 24 trials, 12 for each maze. The order of presentation of the two mazes was pseudo-random (i.e., four random orders counterbalanced between all the participants). For each trial, as soon as the children grasped one of the two tools, the experimented removed the other from the platform. Thus, for each trial, the children could only use one tool to attempt to solve the task.

Results

Results for the percentage of successful trials are shown in **Fig. 2**. To achieve a fine-grained analysis of developmental changes in success, we adopted a Bayesian Generalized Linear Mixed Model (GLMM) approach using the rstanarm package (Gabry & Goodrich, 2017) in R (R Development Core Team, 2011). This Bayesian GLMM was used with Success (i.e., failure [0] or success [1] for each trial) as dependent variable, and Age (in years), Condition (Opaque-Cue *versus* Transparent-Cue *versus* Transparent-No-Cue) and Age*Condition as fixed factors. Subject (i.e., participant's identity), School (i.e., kindergartner's or school's identity), and Trial number (1 to 24) were used as random effects. Estimated parameters are provided in **Table 2**. Age was categorized as a continuous variable (i.e., in days then converted into years) in order to increase the statistical power of the analyses. The children were considered as performing above the chance level when they succeeded on at least 17 of the 24 trials (i.e., about 70% of the trials; binomial test). The Opaque-Cue condition was taken as the intercept (0.61; 95% Credible Interval [CI]: 0.47 to 0.75) and used as a benchmark. This condition was the easiest one, with most of the children performing better than chance from the age of 5 years onwards. Success increased by 0.05 per year (95% CI: 0.02 to 0.07; BF = 37.26). The Transparent-Cue condition (-0.22; 95% CI: -0.43 to -0.02; BF = 0.48) and the Transparent-No-Cue condition (-0.43; 95% CI: -0.63 to -0.22; BF = 62.72) were more difficult than the Opaque-Cue condition. However, as indicated by the Bayes Factors, there was no evidence for a difference between the Opaque-Cue condition and the Transparent-Cue condition, whereas there was very strong evidence that the Transparent-No-Cue condition was more difficult than the Opaque-Cue condition. The Age*Condition interaction was characterized by an increase of 0.03 per year (95% CI: -

0.01 to 0.06; BF = 0.33) in the Transparent-Cue condition and of 0.04 per year (95% CI: 0.01 to 0.07; BF = 0.55) in the Transparent-No-Cue condition. Bayes factors suggest that there was no evidence for the Age*Condition interaction. Taken together, these results indicated that (1) performance increased with age and (2) the Opaque-Cue and Transparent-Cue conditions were easier than the Transparent-No-Cue condition.

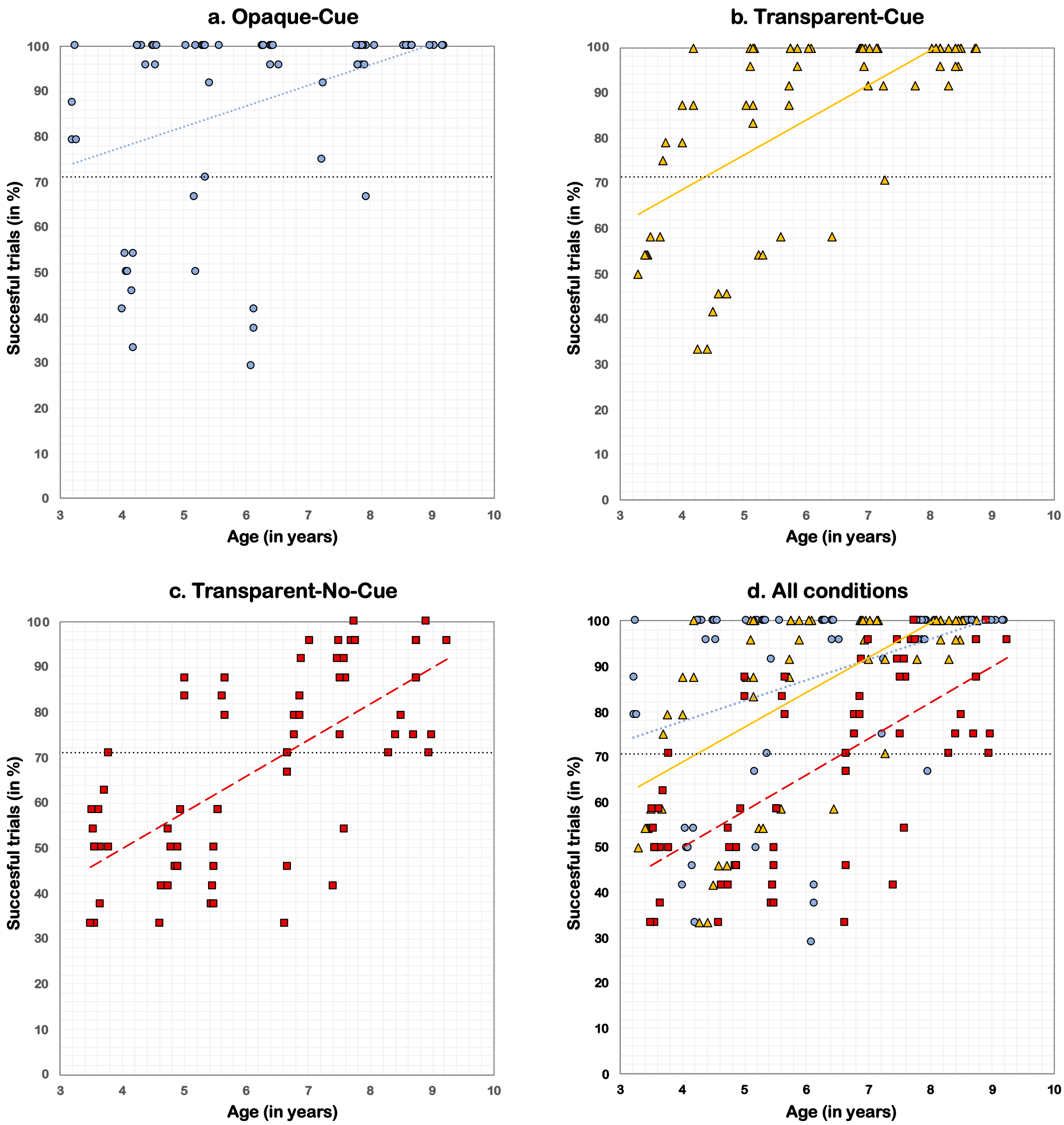

Fig. 2. Percentage of successful trials as a function of age in the Opaque-Cue condition (a), the Transparent-Cue condition (b), the Transparent-No-Cue condition (c), and in all conditions (d). The black dashed line represents chance-level performance (i.e., about 70% (17/24) of successful trials; binomial test). Age was categorized as a continuous variable (i.e., in days then converted into years).

Table 2

*Bayesian GLMM estimates of success by Age, Condition, and Age*Condition*

	Median	L95%	U95%	BF
Opaque-Cue (Intercept)	0.61	0.47	0.75	> 100
Age	0.05	0.02	0.07	37.26
Transparent-Cue	-0.22	-0.43	-0.02	0.48
Transparent-No-Cue	-0.43	-0.63	-0.22	62.72
Age:Transparent-Cue	0.03	-0.01	0.06	0.33
Age:Transparent-No-Cue	0.04	0.01	0.07	0.55

Model formula: Success ~ Age + Condition + Age*Condition + (1|Subject) + (1|School) + (1|Trial number); L95% and U95%, Lower and Upper 95% Credible intervals; BF, Bayes Factors: < 1, no evidence; Between 30 and 100, very strong evidence; > 100, extreme evidence.

We also conducted a trial-by-trial analysis to explore the learning curves in the three conditions. Results for the percentage of successful trials are shown in **Fig. 3**. We adopted a Bayesian Generalized Linear Mixed Model (GLMM) approach using the rstanarm package (Gabry & Goodrich, 2017) in R (R Development Core Team, 2011). This Bayesian GLMM was used with Success (i.e., failure [0] or success [1] for each trial) as dependent variable, and Trial number (1 to 24), Condition (Opaque-Cue *versus* Transparent-Cue *versus* Transparent-No-Cue) and Trial number*Condition as fixed factors. Subject (i.e., participant's identity) and School (i.e., kindergartner's or school's identity) were used as random effects. Estimated parameters are provided in **Table 3**. The Opaque-Cue condition was taken as the intercept (0.92; 95% CI: 0.81 to 1.03) and used as a benchmark. There was no evidence for the effect of Trial number (0.01; 95% CI: 0.01 to 0.01; BF = 0.56). The Transparent-Cue condition (-0.09; 95% CI: -0.18 to -0.01; BF = 0.19) and the Transparent-No-Cue condition (-0.49; 95% CI: -0.60 to -0.39; BF

> 100) were more difficult than the Opaque-Cue condition. However, as indicated by the Bayes Factors, there was no evidence for a difference between the Opaque-Cue condition and the Transparent-Cue condition, whereas there was extreme evidence that the Transparent-No-Cue condition was more difficult than the Opaque-Cue condition. There was no evidence for an interaction effect of Trial number on the Opaque-Cue and Transparent-Cue conditions (-0.01; 95% CI: -0.01 to -0.01; BF = 0.02). However, there was extreme evidence for an interaction effect of Trial number on the Opaque-Cue and Transparent-No-Cue conditions (0.01; 95% CI: 0.01 to 0.02; BF > 100). Taken together, these results indicated that (1) the Transparent-No-Cue condition was more difficult than the Opaque-Cue and Transparent-Cue conditions, and (2) the performance in the Transparent-No-Cue condition increased more steeply across the trials than in the Opaque-Cue and Transparent-Cue conditions.

Table 3

*Bayesian GLMM estimates of success by Trial number, Condition, and Trial number*Condition*

	Median	L95%	U95%	BF
Opaque-Cue (Intercept)	0.92	0.81	1.03	> 100
Trial number	0.01	0.01	0.01	0.56
Transparent-Cue	-0.09	-0.18	-0.01	0.19
Transparent-No-Cue	-0.49	-0.60	-0.39	> 100
Trial number:Transparent-Cue	-0.01	-0.01	0.01	0.01
Trial number:Transparent-No-Cue	0.01	0.01	0.01	> 100

Model formula: Success ~ Trial number + Condition + Trial number*Condition + (1|Subject) + (1|School); L95% and U95%, Lower and Upper 95% Credible intervals; BF, Bayes Factors: < 1, no evidence; > 100, extreme evidence.

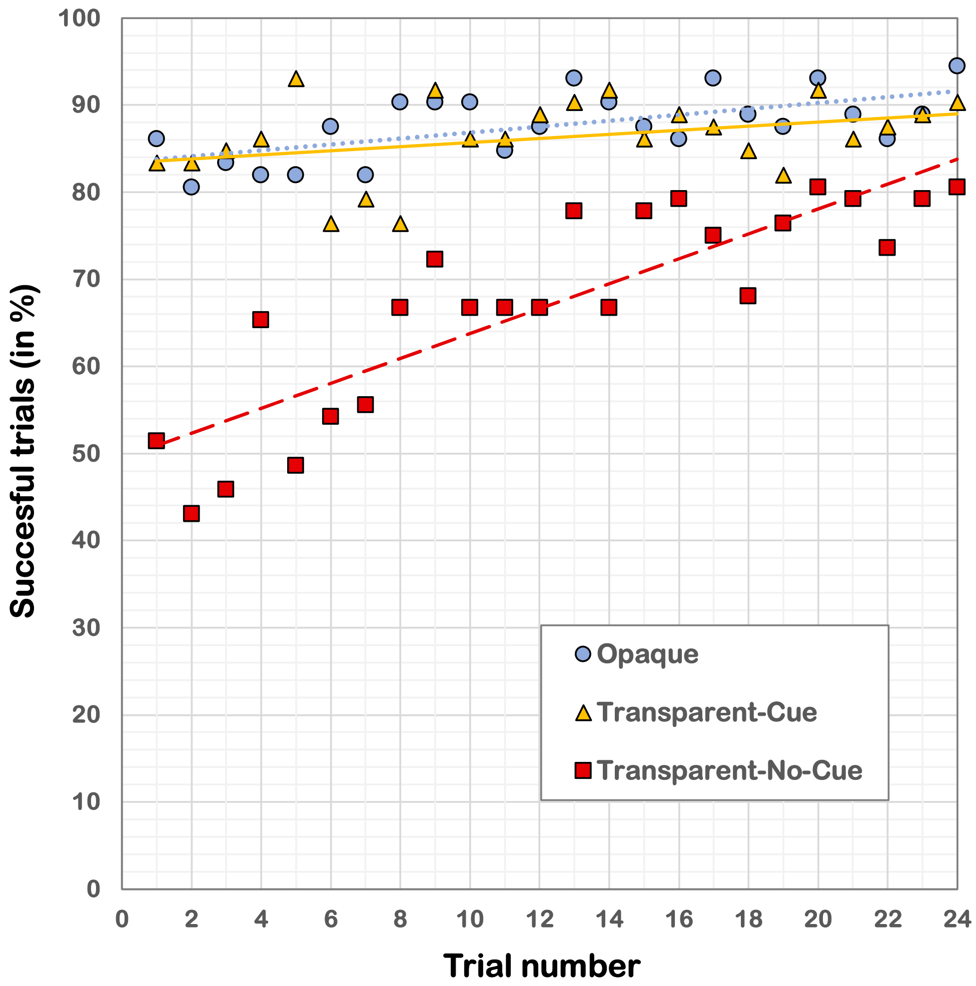

Fig. 3. Percentage of successful trials as a function of trial number in the Opaque-Cue, Transparent-Cue condition and Transparent-No-Cue condition.

Finally, we conducted two additional exploratory analyses to examine the influences of Gender (Female *versus* Male) or Maze (A *versus* B) on success. Again, we adopted a Bayesian Generalized Linear Mixed Model (GLMM) approach using the rstanarm package (Gabry & Goodrich, 2017) in R (R Development Core Team, 2011). This Bayesian GLMM was used with Success (i.e., failure [0] or success [1] for each trial) as dependent variable, and Gender (or Maze) as fixed factor. Subject (i.e., participant's identity), School (i.e., kindergartner's or school's identity), and Trial number (1 to 24) were used as random effects. This analysis revealed that there was no evidence for a difference in terms of gender (0.01; 95% CI: -0.06 to 0.06; BF = 0.02) or maze (0.01; 95% CI: -0.01 to 0.03; BF = 0.01).

Discussion

Our results suggest that technical-reasoning and cued-learning strategies coexist in children and that they manifest differently through development. More specifically, we found that the Opaque-Cue condition was the easiest condition. In this condition, even younger children had to use cued learning to link the cue with the appropriate tool. Therefore, this finding suggests that cued learning can be efficiently performed even early in childhood. The Transparent-No-Cue condition was the most difficult one. Performance in this condition nevertheless increased linearly with age. This finding suggests that representations of physical properties – and, as a result, probably the representations required to solve the present task – are more and more accurate in childhood, progressively improving children's technical-reasoning skills. Finally, one may have expected that the Transparent-Cue condition would be the easiest condition given that the children could potentially use both or either strategy. Surprisingly, children's performance was intermediate in this condition: Better than in the Transparent-No-Cue condition but worse than in the Opaque-Cue condition. Although there was no evidence that the Transparent-Cue condition was more difficult than the Opaque-Cue condition, this finding may suggest that some children chose to reason technically on the physical properties of the task instead of using a more efficient cued-learning strategy, but inadvertently this led them to be less successful. We shall discuss these key findings in turn in the next sections.

The first finding was that cued-learning strategies increased gradually with age, although they were efficient even in younger children, as revealed by the Opaque-Cue condition. Nevertheless, it is noteworthy that a certain number of children, particularly 3- to 4-year-olds, did not perform better than chance in this condition. The literature on observational learning can be particularly useful to interpret the low performance in younger children. A paradigm commonly used in this literature consists in presenting the individual with relevant and irrelevant actions and observes which kinds of actions the individual reproduces. Interestingly, evidence indicates a trend toward increasing overimitation (i.e., imitation of actions that are causally irrelevant to the achievement of a goal; Lyons, Damrosch, Lin, Macris, & Keil, 2011; Lyons, Young, & Keil, 2007; for reviews, see Hoehl et al., 2019; Nielsen, 2018; Over, 2020) over age, with most 2-year-olds exhibiting emulation (i.e., reproducing the result of an action without copying its means) and most 5-year-olds exhibiting overimitation (Horner & Whiten, 2005; McGuigan & Whiten, 2009; McGuigan et al., 2007). A potential interpretation of our findings is that children may progressively develop social-learning strategies, leading them to take into consideration increasingly frequently the intentional actions performed by adults when performing their own actions (McGuigan, 2012). In the Opaque-Cue condition of the present study, the experimenter asked children to perform the two mechanical actions without the ball before beginning the task, mentioned that the cues could be helpful to select the appropriate tool, but did not perform the mechanical actions with the tools. This does not correspond to observational learning. Nevertheless, children had to take into consideration that the cue presented was helpful information provided intentionally by the experimenter. Therefore, we can interpret our findings as if, before the age of 5 years, some children did not consider the experimenter’s intentions as helpful, preventing them from developing an efficient cued-learning strategy consisting in linking the cue with the appropriate tool. Future work is needed to explore this possibility[1].

The second finding is that technical-reasoning skills increased gradually with age, leading most children to be successful only from the age of 8 years onwards in the Transparent-No-Cue condition. A potential alternative to a reasoning-based interpretation is that children used cued learning in this condition. However, if children had followed a cued-learning strategy in the Transparent-No-Cue condition, they should have obtained the same behavioral pattern as the one reported for the Opaque-Cue condition, but they did not. Instead, our findings indicate that understanding that the sliding action results in the ball falling through the aperture or that the rotating action results in the ball rolling down the ramp needs technical reasoning to anticipate the effects of the mechanical actions. In line with this explanation, remember that children could not directly observe the effects of each mechanical action before beginning the task. Furthermore, perhaps this can explain why other works using observational learning have found physical understanding in younger children than those of the present study (e.g., Want & Harris, 2001). Indeed, observational learning could help children acquire abstract physical principles more quickly than situations in which children have to acquire these principles mainly by themselves, including in simple forms of social learning (for discussion about this aspect, see Osiurak, De Oliveira, Navarro, & Reynaud, 2020; Osiurak & Reynaud, 2020; Osiurak et al., 2021). The question is why technical-reasoning skills seem to be much more efficient only from the age of 8 years onwards, which extends other findings indicating that children reliably create

[1] Another simpler interpretation is that children before the age of 5 years were less familiar with iconic graphical symbols such as those used in the present study. As a result, they could have failed to establish the connection between the shape of the arrow and the mechanical action performed by the tool. This interpretation is also consistent with the fact that most of these children had not entered formal schooling, which could have allowed all of them to have experience of interpreting such symbols.

their own tools (i.e., tool innovation; Beck et al., 2011) or reliably use information about the mechanism inside a box to make judgments about what causes a bell to ring (i.e., perception of causality; Schlottmann, 1999) at around 8. Three interpretations can be offered.

The first is that technical-reasoning skills are "inefficient" until this age. This interpretation is however unlikely if we consider the work of Seed and Call (2014), which shows that most of their 3.5-years-olds could solve a physical problem requiring technical reasoning. The discrepancy between their findings and ours in terms of age (i.e., success from the age of 3.5 years in Seed and Call, 2014 *versus* from the age of 8 years in our study) leads us to provide a second interpretation. As explained in the introduction, technical reasoning is based on representations of physical properties. As a result, this the quality and nature of these representations that drive the success in a physical problem. Said differently, a child can attempt to solve a physical problem in reasoning about its physical properties. However, the success depends on the representations of physical properties that the child possesses. Thus, if these representations are not sufficiently elaborated, the child can fail the task or need a certain number of trials (and errors) before improving these representations and, thus, solving the physical problem[2]. In this context, two main factors can explain some discrepancies concerning the age at which a child can solve a physical problem. The first factor is the child' developmental trajectory, which is based on the physical events they can experience over the years and which is mediated by their own individual

[2] This is consistent with trial-by-trial analysis, which revealed that performance in the Transparent-No-Cue condition increased across the trials more steeply than the Opaque-Cue and Transparent-Cue conditions. If we consider that technical-reasoning skills were critical to solve this condition, this finding may confirm that the technical-reasoning strategy is based on the quality of representations of physical properties, which can be improved based on trial and error (i.e., reasoned trial and error; see Vaesen, 2012).

exploration as well as their own social and cultural environment (for studies exploring the effect of culture, see e.g., Neldner et al., 2017; Neldner et al., 2019). Thus, this interindividual variation can explain why some 5-years-olds performed better than chance in the Transparent-No-Cue. The second factor is the difficulty of the task in terms of physical understanding, which remains nevertheless necessarily determined by the first factor. This can explain the aforementioned discrepancy between Seed and Call's (2014) results and ours. A third interpretation is that most of the children aged below 8 years in the present study could have failed the Transparent-Cue condition not because of limited technical-reasoning skills but because of executive-function limitations. One concern though is that researchers have failed to find a link between poor performance on tool-innovation tasks and executive-function capacities such as flexibility or impulsivity (Chappell et al., 2013; although see Gönül et al., 2018, for a link between executive-function capacities and tool making after social learning). To sum up, further work is needed to explain why the understanding of physical principles has such high age-related variability in the literature.

The third finding is that children, or at least some children, might engage in technical-reasoning strategies even when their technical-reasoning skills are not developed enough to reach high levels of performance compared to the use of cued learning. Indeed, the fact that children were less successful until the age of 7 years in the Transparent-Cue condition than in the Opaque-Cue condition suggests that the opportunity to see the mechanical actions associated with the two tools interfered with their cued learning. This supports the idea that humans might have an appetence for understanding physical events or, said differently, a kind of technical curiosity (Osiurak et al., 2020; Osiurak & Reynaud, 2020). Consistent with this, evidence indicates that people can perform relevant but unnecessary tool-use actions when solving mechanical problems, such as making an additional hook to extract a target (Lesourd et al., 2016). Interestingly, patients with semantic dementia or Alzheimer's disease can also exhibit this behavior (Lesourd et al., 2016). This is also in line with studies showing that humans might prefer to use a tool even when it is less efficient than doing without it (e.g., Osiurak, Morgado, Vallet, Drot, & Palluel-Germain, 2014). However, such a bias is not observed in New-Caledonian crows (Danel, Osiurak, & von Bayern, 2017), a tool-using species which is known for its remarkable tool-using and physical-understanding skills (Hunt, 1996; Rutz & St Clair, 2012). Future research is needed to explore how this hypothetical technical curiosity could develop in childhood.

To conclude, we would like to discuss the implications of our findings for the literature on tool use. Our findings indicate that children, but more generally humans, can use both technical-reasoning and cued-learning strategies to use tools. Put simply, the physical characteristics of tools could explain why we sometimes use one strategy over the other. More specifically, the development of cumulative technological culture in humans has led to the proliferation of opaque tools, namely tools whose making – and even sometimes the functioning – is completely opaque for the user. This is the case, for instance, of interface-based technologies, which consist in pressing buttons in arbitrary fashion (e.g., TVs, touchscreens). For this category of tools, cued learning might be sufficient to use them effectively, explaining why very young children or even non-tool-using species such as baboons can use them (Claidière, Smith, Kirby, & Fagot, 2014). However, physical tools such as knives, hammers, or even early stone tools might require technical reasoning if only to select the appropriate one to perform a given task. In sum, our results provide an interesting insight into the cognitive development of tool use in childhood and the strategies underlying tool use in humans. They also raise the question of whether the more and more frequent recruitment of cued learning to use interface-based technologies over the years interferes with the developmental trajectory of the acquisition of technical-reasoning skills.

References

Beck, S. R., Apperly, I. A., Chappell, J., Guthrie, C., & Cutting, N. (2011). Making tools isn't child's play. *Cognition, 119*, 301–306.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge: MIT Press.

Chappell, J., Cutting, N., Apperly, I. A., & Beck, S. R. (2013). The development of tool manufacture in humans: What helps young children make innovative tools? *Philosophical Transactions of the Royal Society B, 368*, 20120409.

Claidière, N., Smith, K., Kirby, S., & Fagot, J. (2014). Cultural evolution of systematically structured behaviour in a non-human primate. *Proceedings of the Royal Society of London B, 281*, 20141541.

Cutting, N., Apperly, I. A., & Beck, S. R. (2011). Why do children lack the flexibility to innovate tools? *Journal of Experimental Child Psychology, 109*, 497–511.

Cutting, N., Apperly, I. A., Chappell, J., & Beck, S. R. (2014). The puzzling difficulty of tool innovation: Why can't children piece their knowledge together? *Journal of Experimental Child Psychology, 125*, 110–117.

Danel, S., Osiurak, F., & von Bayern, A. M. P. (2017). From the age of 5 humans decide economically, whereas crows exhibit individual preferences. *Scientific Reports, 7*, 17043.

Gabry, J., & Goodrich, B. (2017). rstanarm: Bayesian applied regression modeling via Stan. R package version 2.15.3 (Retrieved from http://mc-stan.org/rstanaram/).

Goldenberg, G., Daumüller, M., & Hagmann, S. (2001). Assessment of therapy of complex activities of daily living in apraxia. *Neuropsychological Rehabilitation, 11*, 147–169.

Goldenberg, G., & Hagmann, S. (1998a). Therapy of activities of daily living in patients with apraxia. *Neuropsychological Rehabilitation, 8*, 123–141.

Goldenberg, G., & Hagmann, S. (1998b). Tool use and mechanical problem solving in apraxia. *Neuropsychologia, 36*, 581–589.

Goldenberg, G., & Spatt, J. (2009). The neural basis of tool use. *Brain, 132*, 1645–1655.

Gönül, G., Tamaz, E. K., Hohenberger, A., & Corballis, M. (2018). The cognitive ontogeny of tool making in children: The role of inhibition and hierarchical structuring. *Journal of Experimental Child Development, 173*, 222–238.

Gruber, T. (2016). Great apes do not learn novel tool use easily: Conservatism, functional fixedness, or cultural influence? *International Journal of Primatology, 37*, 296–316.

Hartmann, K., Goldenberg, G., Daumüller, M., & Hermsdörfer, J. (2005). It takes the whole brain to make a cup of coffee: The neuropsychology of naturalistic actions involving technical devices. *Neuropsychologia, 43*, 625–627.

Hermann, E., Wobber, V., & Call, J. (2008). Great apes' (*Pan troglodytes, Pan paniscus, Gorilla gorilla, Pongo pygmaeus*) understanding of tool functional properties after limited experience. *Journal of Comparative Psychology, 122*, 220–230.

Hoehl, S., Keupp, S., Schleihauf, H., McGuigan, N., Buttelmann, D., & Whiten, A. (2019). 'Over-imitation': A revie and appraisal of a decade of research. *Developmental Review, 51*, 90–108.

Horner, V. & Whiten, A. (2005). Causal knowledge and imitation/emulation switching in chimpanzees (*Pan troglodytes*) and children. *Animal Cognition, 8*, 164–181.

Hunt, G. R. (1996). Manufacture and use of hook-tools by New Caledonian crows. *Nature, 379*, 249

Hunt, G. R., Gray, R. D., & Taylor, A. H. (2013). Why is tool use rare in animals? In C. Sanz, J. Call, & C. Boesch (eds.), *Tool use in animals: cognition and ecology* (pp. 89–118). Cambridge: Cambridge University Press.

Jarry, C., Osiurak, F., Delafuys, D., Chauviré, V., Etcharry-Bouyx, F. *et al.* (2013). Apraxia of tool use: More evidence for the technical reasoning hypothesis. *Cortex, 49*, 2322–2333.

Lesourd, M., Baumard, J., Jarry, C., Etcharry-Bouyx, F., Belliard, S., Moreaud, O., Croisile, B., Chauviré, V., Granjon, M., Le Gall, D., & Osiurak, F. (2016). Mechanical problem-solving in Alzheimer's disease and semantic dementia. *Neuropsychology, 30*, 612–623.

Lyons, D. E., Damrosch, D. H., Lin, J. K., Macris, D. M., & Keil, F. C. (2011). The scope and limits of overimitation in the transmission of artefact culture. *Philosophical Transactions of the Royal Society B, 366*, 1158–1167.

Lyons, D. E., Young, A. G. & Keil, F. C. (2007). The hidden structure of overimitation. *Proceedings of the National Academy of Sciences USA, 104*, 19751–19756.

Mandler, J. M. (2004). *The foundations of mind: Origins of conceptual thought*. New York: Oxford University Press.

Martin, M., Beume, L., Kümmere, D., Schmidt, C. S. M., Bormann, T. *et al.* (2016). Differential roles of ventral and dorsal streams for conceptual and production-related components of tool use in acute stroke patients. *Cerebral Cortex, 26*, 3754–3771.

Martin-Ordas, G., Call, J., & Colmenares, F. (2008). Tubes, tables and traps: Great apes solve two functionally equivalent trap tasks but show no evidence of transfer across tasks. *Animal Cognition, 11*, 423–430.

Martin-Ordas, G., Jaek, F., & Call, J. (2012). Barriers and traps: Great apes' performance in two functionally equivalent tasks. *Animal Cognition, 15*, 1007–1013.

McGuigan, N. (2012). The role of transmission biases in the cultural diffusion of irrelevant actions. *Journal of Comparative Psychology, 126*, 150–160.

McGuigan, N., & Whiten, A. (2009). Emulation and "overemulation" in the social learning of causally opaque versus causally transparent tool use by 23- and 30-month-old children. *Journal of Experimental Child Psychology, 104*, 367–381.

McGuigan, N., Whiten, A., Flynn, E. F., & Horner, V. (2007). Imitation of causally opaque versus causally transparent tool use by 3- and 5-year old children. *Cognitive Development, 22*, 353–364.

Neldner, K., Mushin, I., & Nielsen, M. (2017). Young children's tool innovation across culture: Affordance visibility matters. *Cognition, 168*, 335–343.

Neldner, K., Redshaw, J., Murphy, S., Tomaselli, K., Davis, J., Dixson, B., & Nielsen, M. (2019). Creation across culture: Children's tool innovation is influenced by cultural and developmental factors. *Developmental Psychology, 55*, 877–889.

Nielsen, M. (2018). The social glue of cumulative culture and ritual behavior. *Child Development Perspectives, 12*, 264–268.

O'Neill, L., Picaud, A., Maehner, J., Gahr, M., & von Bayern, A. M. P. (2019). Two macaw species can learn to solve an optimised two-trap problem, but without functional causal understanding. *Behaviour*, *156*, 691–720.

Osiurak, F., De Oliveira, E., Navarro, J., & Reynaud, E. (2020). The castaway island: Distinct roles of theory of mind and technical reasoning in cumulative technological culture. *Journal of Experimental Psychology: General, 149*, 58–66.

Osiurak, F., Jarry, C., Allain, P., Aubin, G., Etcharry-Bouyx, F., Richard, I., Bernard, I., & Le Gall, D. (2009). Unusual use of objects after unilateral brain damage: The technical reasoning model. *Cortex, 45*, 769–783.

Osiurak, F., Jarry, C., Lesourd, M., Baumard, J., & Le Gall, D. (2013). Mechanical problem-solving in left brain-damaged patients and apraxia of tool use. *Neuropsychologia, 51*, 1964–1972.

Osiurak, F., Jarry, C., & Le Gall, D. (2010). Grasping the affordances, understanding the reasoning: Toward a dialectical theory of human tool use. *Psychological Review, 117*, 517–540.

Osiurak, F., Lasserre, S., Arbanti, J., Brogniart, J., Bluet, A., Navarro, J., & Reynaud, E. (2021). Technical reasoning is crucial to avoid reinventing the wheel. *Nature Human Behaviour, in press*.

Osiurak, F., Lesourd, M., Navarro, J., & Reynaud, E. (2020). Technition: When tools come out of the closet. *Perspectives on Psychological Science, 15*, 880–897.

Osiurak, F., Morgado, N., Vallet, G. T., Drot, M., & Palluel-Germain, R. (2014). Getting a tool gives wings: Underestimation of effort for tool use. *Psychological Research, 78*, 1–9.

Osiurak, F., & Reynaud, E. (2020). The elephant in the room: What matters cognitively in cumulative technological culture. *Behavioral and Brain Sciences, 43*, e156.

Over, H. (2020). The social function of imitation in development. *Annual Review of Developmental Psychology, 2*, 93–109.

Penn, D. C., Holyoak, K. J., & Povinelli, D. J. (2008). Darwin's mistake: Explaining the discontinuity between human and nonhuman minds. *Behavioral and Brain Sciences, 31*, 109–130.

Penn, D. C., & Povinelli, D. J. (2007). Causal cognition in human and nonhuman animals: A comparative, critical review. *Annual Review of Psychology, 58*, 97–118.

Povinelli, D. J. (2000). *Folk physics for apes*. New York: Oxford University Press.

Povinelli, D. J., & Frey, S. H. (2016). Constraints on the exploitation of the functional properties of objects in expert tool-using chimpanzees (*Pan troglodytes*). *Cortex, 82*, 11–23.

R Development Core Team (2011). R: A language and environment for statistical computing. R Foundation for Statistical Computing.

Remigereau, C., Roy, A., Costini, O., Osiurak, F., Jarry, C., & Le Gall, D. (2016). Involvement of technical reasoning more than functional knowledge in development of tool use in childhood. *Frontiers in Psychology, 7*, 1625.

Reynaud, E., Lesourd, M., Navarro, J., & Osiurak, F. (2016). On the neurocognitive origins of human tool use: A critical review of neuroimaging data. *Neuroscience & BioBehavioral Reviews, 64*, 421–437.

Reynaud, E., Navarro, J., Lesourd, M., & Osiurak, F. (2019). To watch is to work: A critical review of neuroimaging data on Tool-use Observation Network (ToON). *Neuropsychology Review, 29*, 484–497.

Rutz, C., & St Clair, J. J. H. (2012). The evolutionary origins and ecological context of tool use in New Caledonian crows. *Behavioural Processes, 89*, 153–165 (2012).

Salazar-Lopez, E., Schwaiger, B. J., & Hermsdörfer, J. (2016). Lesion correlates of impairments in actual tool use following unilateral brain damage. *Neuropsychologia, 84*, 167–180.

Schlottmann, A. (1999). Seeing it happen and knowing how it works: How children understand the relation between perceptual causality and underlying mechanism. *Developmental Psychology, 35*, 303–317.

Seed, A. M., & Call, J. (2014). Space or physics? Children use physical reasoning to solve the trap problem from 2.5 years of age. *Developmental Psychology, 50*, 1951–1962.

Shumaker, R. W., Walkup, K. R., & Beck, B. B. (2011). *Animal tool behavior*. Baltimore: John Hopkins University Press.

Vaesen, K. (2012). The cognitive bases of human tool use. *Behavioral and Brain Sciences, 35*, 203–218.

Visalberghi, E., & Limongelli, L. (1994). Lack of comprehension of cause-effect relations in tool-using capuchin monkeys (*Cebus apella*). *Journal of Comparative Psychology, 108*, 15–22.

Want, S. C., & Harris, P. L. (2001). Learning from other people's mistakes: Causal understanding in learning to use a tool. *Child Development, 72,* 431–443.

Weir, A. S., Chappell, J., & Kacelnik, A. (2002). Shaping of hooks in New Caledonian crows. *Science, 297*, 981.

Wolpert, L. (2003). Causal belief and the origins of technology. *Philosophical Transactions of the Royal Society A, 361*, 1709–1719.

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Code availability

Codes used in this study are available at https://osf.io/k83t5/

Data availability

The data that support the findings of this study are available at https://osf.io/k83t5/