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Of babies and birds: complex tool behaviours are not sufficient for the evolution of the ability to create a novel causal intervention

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Humans are capable of simply observing a correlation between cause and effect, and then producing a novel behavioural pattern in order to recreate the same outcome. However, it is unclear how the ability to create such causal interventions evolved. Here, we show that while 24-month-old children can produce an effective, novel action after observing a correlation, tool-making New Caledonian crows cannot. These results suggest that complex tool behaviours are not sufficient for the evolution of this ability, and that causal interventions can be cognitively and evolutionarily disassociated from other types of causal understanding.

1. Introduction

Recent work in psychology, philosophy and computer science has highlighted the power of causal interventions: the ability to learn a cause–effect relationship using only observed correlations, and then act to take advantage of that cause–effect relationship [1–3]. Causal interventions can be considered a two-stage process: (i) an agent infers a cause–effect relationship from observation alone and (ii) the agent creates a new behaviour to recreate the effect observed, using the causal knowledge gained through observation. Imagine, for example, that an agent observes a box dispense food when a block is on top of it, and not do so when the block is not on the box top. If the agent is capable of inferring from these observations that the relationship of ‘contact’ between the block and box causes the food to appear, then it can subsequently act itself to obtain the effect by putting the block back on top of the box to make it dispense food. Thus, it can *intervene* on the causal structure of the world it has inferred to exist. By contrast, an agent only capable of operant conditioning would behave rather differently. It would need to learn through its own actions that picking up the block and putting it onto the box caused the food to be dispensed. Without an associatively learnt link between its own behaviour and a positive outcome, it would do nothing [4]. Thus, observing the block on top of the box or next to it would not lead the agent to generate the novel behaviours of picking up the block and putting it on top of the box.

The ability to create a wide range of causal interventions is one of the key factors behind our transition from nut-cracking hominins to humans of science and civilization. We treat observed correlations as indicators of causal relationships, and then use that causal information to design actions that shape the world to our advantage. This ability not only increases our behavioural flexibility, but also our understanding of opaque cause–effect relationships. When an effect appears to have two potential causes, an agent capable of causal interventions can seek to recreate each of these potential causes in

isolation and then observe which leads to the effect. The ability to intervene is therefore the cornerstone of the scientific method [3,5–8].

By the age of 24 months, human infants are able to design novel causal interventions from observed correlations if the correlated events they observe involve direct spatial contact, are described using causal language or are an outcome of the intentional actions of other agents [1,9]. At around 4 years of age, children become able to causally intervene more generally. For example, children will infer causal relations when they observe two events that are linked temporally but not by physical contact [2,9,10], and when they observe correlations between events that simply occur naturally and are not the outcome of intentional actions. Moreover, they will design appropriate novel interventions when they infer more complex causal structures, differentiating, for example, between the appropriate actions on common causes or causal chains [11].

It has long been suggested that there is an evolutionary link between tool behaviours and causal understanding [12]. Clearly, an animal that understands the causal underpinning of its tool use will be a more flexible tool user and maker than one without such understanding, as it can adapt its tools to novel situations. New Caledonian crows (*Corvus moneduloides*) produce sophisticated tool behaviours both in the wild [13–15] and in captivity [16–23]. This species is therefore an ideal candidate for testing whether the ability to create causal interventions is linked evolutionarily to complex tool behaviours. Recent work by von Bayern *et al.* [23] raises the possibility that New Caledonian crows are capable of creating a causal intervention. After being given the experience of pushing down a platform with their beak to obtain food, these crows then spontaneously dropped a stone onto the platform to obtain food when the platform was out of reach.

While there are several explanations for this behaviour, one possibility is that these crows inferred that the link between beak-pushing and the platform being triggered was the causal relation of ‘contact’ and then identified that the behaviour of dropping the stone on the platform would also create the same contact relation. However, the ability to causally intervene requires the identification of a causal relation *by observation alone*. There are at least two ways in which agents can be involved with a causal interaction. First, they can set something in motion and then observe the downstream effects (i.e. they perform an action, then a causal interaction happens *afterwards*). Second, they can *themselves* be part of the interaction (e.g. the interaction is between beak and platform). In this sense, the causal interaction is not *observed but experienced*. The question therefore arises whether the same pattern of performance would be obtained if the crows observed an interaction between two external objects (i.e. a falling block causing the platform to depress), rather than experienced an interaction between their body and an external object (i.e. causing the platform to depress via beak-pushing). If so, this would be evidence for a causal intervention, as the crows would be inferring a causal relationship from observation alone.

We presented New Caledonian crows and 24-month-old infants with a novel paradigm developed from the example of the block and the box mentioned above. Subjects initially accidentally caused a block to fall onto a platform. This caused the platform to rotate and food to fall from the box.

Thus, while a behaviour (pushing the block) was rewarded, the interaction between block and platform was only observed. Subjects therefore *experienced* that a pushing action was followed a short time later with food, but only *observed* that their action was mediated by an indirect effect: that the falling block turned the platform and so dispensed the food. Subjects never directly experienced turning the platform to gain food in our study, unlike in the study of von Bayern *et al.* [23], where crows directly pushed a platform with their beak. This difference is critical. In our study, the crows’ behaviour was no longer proprioceptively linked to the key causal interaction of making the platform move. Instead, it was linked to acting on the block alone. Therefore, if subjects were capable of operant conditioning, then they should perform only the rewarded pushing behaviour on the block. By contrast, if subjects were able to use their observation of the interaction to infer that the contact between the block and platform actually dispensed the food, then they should be able to create a new behavioural pattern—that is, pick up the block when next to the apparatus and insert it into the correct hole in the apparatus.

2. Material and methods

We carried out the experiment with eight wild crows captured on the island of Maré, New Caledonia and 22 children within two weeks of their second birthday (mean = 24.07 months, s.d. = 6 days). The crows were housed in a five-cage outdoor aviary close to the location of capture; the cages varied in size but were all at least 8 m² in area and 3 m high. The testing cage was visually isolated from the other cages. Five of the crows were adults more than 2 years old, and three were subadults less than 2 years old. Based on sexual size dimorphism [24], two were females. All crows were released at their site of capture after testing. The corvid study was carried out under the ethics approval of the University of Auckland (reference no. R602). Children were recruited from the University of Washington’s (UW) participant pool and tested at the UW Institute for Learning and Brain Sciences under ethics approval (reference no. 43070). Pre-established criteria for admission into the study were that the children be full term and normal birth weight, and have no known developmental concerns. Eleven of the 22 children tested were female. Additional children were excluded from the final sample owing to experimenter error ($n = 1$) and technical issues with the apparatus such as the ball or block becoming stuck during an observation trial, or subjects putting their hands into the holes of the box ($n = 14$).

All subjects of both species were presented with a puzzle box (figure 1). This was a clear, Plexiglas box (22 × 22 × 20.5 cm) with six rectangular holes into which an object could be inserted. From the subject’s perspective, two upper holes were located on the back side of the box (7.5 × 3 cm), one upper hole (6 × 3 cm) and two lower holes on the front side of the box (4 × 10.5 cm), and one upper hole on the left side of the box (4 × 3 cm). The puzzle box housed an opaque weighted cylinder with a platform on which a reward could be placed. The weight of the reward alone was not enough to rotate the weighted cylinder. However, if a white plastic block (2.5 × 1 × 4.5 cm) was inserted into the correct hole (the hole on the left-hand side of the box), then it would fall on the cylinder platform, causing the cylinder to rotate and allowing both the plastic block and the reward to pass through an opening at the box’s base. The other five holes served as a control for trial-and-error learning. If subjects randomly inserted the block into the apparatus as part of their exploratory behaviour, then we expected them to not initially choose the correct hole more often than chance (1/6).

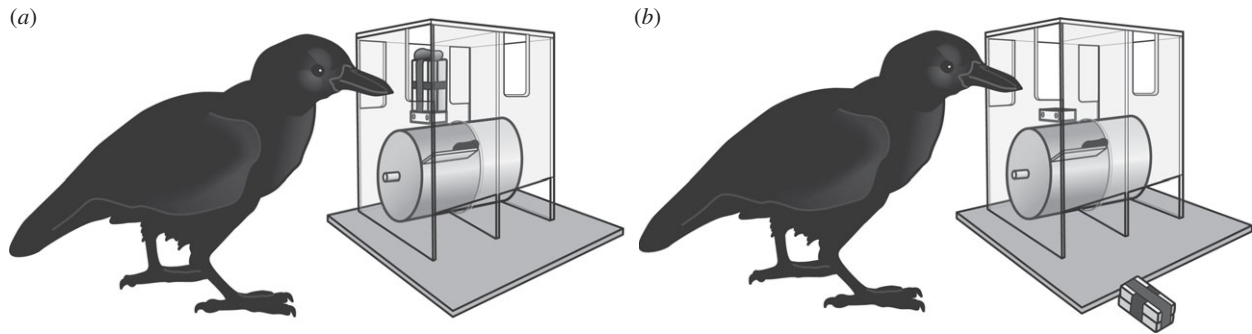


Figure 1. Diagram of the experimental apparatus. If the block is inserted into the hole on the upper left side of the apparatus or pushed from the ledge underneath this hole, then it falls onto the platform. This causes the platform to revolve and dispense either meat (crow experiment) or a marble (child experiment). Inserting the block into the five other holes in the apparatus (two on the back, three on the front) does not cause the platform to revolve.

(a) New Caledonian crows

Crows were first habituated to the Plexiglas box and the plastic block by our placing these objects in the crows' home cages for 3 days and baiting them with meat twice a day. The crows were then randomly assigned to two groups: the intervention group and the operant group. The intervention group observed the causal interaction following their actions (observation trial), and then were given the opportunity to perform an intervention to recreate the causal interaction (experimental trial), whereas the operant group was rewarded through a shaping procedure for the actions required to solve the experimental trial. This allowed us to both contrast these two different types of cognition, and ensure (using the operant group) that it was possible for the crows to learn the behaviours required to solve an experimental trial.

The intervention group consisted of five crows, three of which were adults and two of which were female (one adult, one juvenile). This group was presented with two types of trials: observation and experimental trials. In observation trials, the plastic block was placed on a ledge inside the box below the target hole and meat was attached to it with wire. A second piece of meat was placed on the cylinder platform. When the crows pulled the meat attached to the block, they caused the block to fall off the ledge and onto the cylinder platform, which would then rotate, causing the block and the meat placed on the cylinder platform to pass through an opening at the box's base (see figure 1; the electronic supplementary material, movie S1). In experimental trials, the block was placed on the ground in front of the apparatus and a single piece of meat was placed on the cylinder platform inside the apparatus. Unlike an observation trial, on experimental trials, the block itself was not baited. To gain access to the meat on experimental trials, the crows had to pick up the block, insert it into the target hole on the left-hand side of the box and then drop it (see figure 1; electronic supplementary material, movie S1). Trials were run in blocks of ten 2 min trials: five observation and five experimental. The 2 min response period for crows began when the crow landed on the perch closest to the puzzle box. Trial order within each block was pseudo-randomized (no more than two trials of one condition in a row), with one constraint: that the first trial in the first block of trials was an experimental trial. This was carried out to establish that the subjects did not know how to solve the puzzle box task at baseline. Testing stopped if the crows solved the problem in the experimental condition, or after 20 blocks (200 trials in total, 100 of each condition). The apparatus was occluded between trials.

The operant group consisted of three male crows, two of which were adult. Crows in this group were first presented with five baited observation trials (the same as described above) followed by an unbaited observation trial where the block was placed inside the apparatus on the ledge but not baited with meat. Crows were given blocks of six trials (five baited, one unbaited) until they started pushing the plastic

block on the unbaited trial. Once crows pushed the block in the unbaited trial they were no longer presented with baited trials, and were instead presented with a series of unbaited trials until they had successfully retrieved the food in five successive trials (criterion). Once this criterion was reached, the location of the plastic block was changed, and the process was repeated, starting with five baited trials and one unbaited trial, until the crows reached criterion with the block in the new location (shaping). The changes in the location of the block followed the same pattern for each crow. After the initial trials on which the block was located on the ledge below the target hole, the block was then positioned half inside the apparatus and half on a ramp abutting the box, then fully on the ramp, then fully on a lowered ramp, then on the floor outside the box beneath the target hole and then on the floor in the experimental trial position (figure 1). Crows therefore learnt first to push, then flip and finally to lift the block into the hole. Training for the operant group finished once the crows had solved the task with the block in the experimental trial position on five consecutive trials.

(b) Twenty-four-month-old children

Children were tested in the intervention group only, since pilot work revealed they did not require the type of shaping described above for the crows to solve the task. The procedure followed the same general procedure as with the crows, using the same apparatus, save that the desirable meat was replaced with a desirable marble for the children to play with. Subjects sat on their carer's lap at a table across from the experimenter and were told that they would be playing a ball game. First, children were presented with a ball (a marble) and encouraged to place it in a toy marble run. This gave the children motivation to gain access to the ball. Once the child had placed the ball in the marble run, the experimenter asked the child if he or she would like to try to get more balls by playing the ball game.

Each trial started when the experimenter lifted an opaque occluder to reveal the puzzle box with a marble inside, and then pushed a tray with the puzzle box over to the child. The moment the child touched either the block or the puzzle box, a 30 s trial began. Pilot work had established that response periods longer than 30 s caused children to become bored. During the trial, children were encouraged to 'get the ball', but to refrain from putting their hands in any of the holes on the box. The experimenter used general phrases to bring the child's attention to the marble (e.g. 'where's the little ball?', 'do you see the little ball?', 'it's your turn to get the ball'). These phrases were used across all trials to motivate children to interact with the task. However, such prompting is unlikely to have given the children any significant advantage, because, just as for the crows, the children were not provided with any information about the action required to solve the task.

Just as with the crows in the intervention group, two types of trials were presented to the children: observation and experimental trials. On observation trials, a ball was attached to the block and then placed on the inner ledge below the target hole. A second ball was placed on the cylinder platform inside the box. When children attempted to retrieve the ball attached to the block, they would accidentally knock the block off the inner ledge and onto the cylinder platform, causing the block and both balls to pass through the opening at the box's base. The child could then place the balls in the marble run. On experimental trials, a single ball was placed on the cylinder platform inside the puzzle box, and the plastic block was placed in front of the puzzle box (figure 1). If the child did not solve the task on an experimental trial within the 30 s response period, then the experimenter said, 'Should we try something else?', pulled the tray away and placed the occluder on the table in front of the puzzle box.

Trials were run in blocks of 10 trials, with each child participating in up to two blocks of trials (20 trials). Between the two blocks of trials, the experimenter removed the apparatus and engaged the child in a short break during which the child and the experimenter played with a small plastic toy for 40–50 s. Testing ended once children either solved one experimental trial, stopped participating owing to frustration or completed 20 trials. Consequently, children could receive a different number of trials depending on their performance.

3. Results

All crows in the intervention group gained the meat piece placed on the platform on every observation trial. However, on experimental trials, none of the five crows tested inserted the block into the apparatus in order to gain the same meat piece in any of the 100 trials they received of this condition (see electronic supplementary material, movie S1). In observation trials, crows switched from pulling at the food to simply pushing the block into the apparatus very quickly (mean trials \pm s.e.: 11.2 ± 6.1). Approach time to the testing area did not significantly change between the first and 20th block of the observation trials (paired *t*-test: $t = 0.25$, $p = 0.81$), but did between the first and 20th block of the experimental trials (paired *t*-test: $t = -7.86$, $p = 0.002$). Thus, by the end of the experiment, the crows had learnt not to approach the apparatus on experimental trials. Within the first two blocks of the experimental trials, all five crows touched the block at least once, four of the five pushed the block at least once, and three of the five actually picked up and then dropped the block at least once (one adult and the two juveniles). By contrast, in the final two blocks of the experimental trials, no crow interacted with the block in any way. Thus, there was a significant difference in the proportion of trials the crows interacted with the block between the first 10 experimental trials and the last 10 experimental trials (paired *t*-test: $t = 4.09$, $p = 0.015$). By contrast, all three crows in the operant group gained the platform meat piece when the block was in the experimental trial location. These crows took on average 111.7 ± 55.2 trials to solve the task, of which 83.7 ± 32.7 trials were rewarded (see electronic supplementary material, movie S1). Thus, no crow in the intervention group produced an intervention despite receiving, on average, more rewarded trials than the operant group. Across the coding of the crow data $\kappa = 0.90$.

Just as with the crows, all children gained the marble placed on the platform on every observation trial. In contrast

to the crows, 16 of the 22 children tested (72.7%) correctly solved the task on an experimental trial by inserting the block into the apparatus in order to gain access to the marble placed on the platform. One of these children solved the task on the first experimental trial, without having seen an observation trial. This child was excluded from further analysis. The performance of the children in experimental trials was significantly different from that of the crows, who never gained the platform reward item placed on the platform on an experimental trial (Fisher's exact test: $p < 0.01$). On average, the 15 children who solved the task (excluding the spontaneous solver) did so after six trials: three experimental and three observation (mean \pm s.e.: total trials: 6.2 ± 0.28 ; experimental trials: 2.7 ± 0.20 ; observation trials: 3.5 ± 0.20). Of the six children that did not solve the task, two became frustrated and asked to discontinue the study, and four children completed both blocks of trials without ever solving an experimental trial.

We conducted an in-depth behavioural analysis of the children's performance ($n = 20$; one child had to be excluded from the in-depth analysis due to a lack of video recording). On the first experimental trial, only one child interacted with the block on the table (using the block to hit the box, after trying to open the top of the box). Children instead attempted other behaviours on the first trial, including putting their hands into the holes of the box (10 of 20), trying to open the top of the box (4 of 20) and asking for help (1 of 20). The remaining five children tactfully explored the stimuli, but did not attempt to solve the problem.

Of the 20 children, 14 solved the task on an experimental trial. On average, these children needed to observe the effect of their own accidental actions 4.77 ± 1.20 times before they were able to create an intervention. Prior to solving the task by performing the target behaviour, five of the 14 successful children put the block into one of the five incorrect holes in the box during an experimental trial. These five children therefore may have been using trial-and-error learning to solve the problem. However, of the children who solved the task, significantly more than expected by chance chose to insert the block only into the correct hole, without first inserting it into any other hole (binomial test: $p < 0.001$, $n = 14$, two-tailed). On all but the in-depth behavioural analysis, the two coders were in perfect agreement ($\kappa = 1.0$). On the in-depth behavioural analysis, $\kappa = 0.85$.

4. Discussion

Our results provide no evidence that New Caledonian crows can create a causal intervention. Even after observing the block cause the platform to move and so dispense food from the box 100 times, New Caledonian crows did not pick up the block and insert it into the puzzle box. Instead, crows in the intervention group learnt two behaviours: to push the block in the observation condition when it was on the ledge inside the apparatus and, as the changes in approach latency show, to not interact with the block in the experimental condition when it was positioned on the table. Thus, the crows learnt to reproduce the accidental action that had been rewarded, as we might expect from the operant conditioning literature, but did not learn to produce the novel action of lifting and inserting the block on the experimental trials. Importantly, the performance of the crows in the operant group demonstrates that this failure was not because the

crows were unable to perform the motor actions necessary to solve the task. Crows in the operant group were able to learn the behaviours required, but could only do so when each stage of the required action was rewarded.

By contrast, our results show that by 24 months of age children are able to create a causal intervention after observing the effect of their own accidental action. This was not a trivial cognitive task for the children to solve, however. Approximately 18% of the children tested did not create an intervention, despite being motivated for the entire duration of the experiment. Moreover, a portion of the children who were successful (5/14) inserted a block into a hole other than the target hole before solving the problem. Even the nine successful children who performed only the target behaviour had to observe the effect of the block hitting the platform approximately five times, on average, before they created an intervention.

It is clear that the difference in performance between crows and infants was not due to motivation. The crows were highly motivated in the initial trials of the experiment and maintained their level of motivation in the observation trials across the course of the experiment, as shown by the lack of difference in approach times between the initial and last 20 observation trials. The reduction in approach time was specific only to the later experimental trials (as shown by the difference in approach times between the first and last 20 experimental trials). This indicates it was the crows' failure to be able to generate a causal intervention that led them to instead learn not to approach as quickly on the experimental trials, rather than an initial lack of motivation to interact with the apparatus on experimental trials.

The crows' performance on this task was similar to this species's performance on similar problems presented in previous studies. New Caledonian crows do not spontaneously drop stones into a water-filled tube (the Aesop's fable task), but are able to learn to do so via shaping [18]. Similarly, crows in the present task did not spontaneously insert an object into an opening to solve the platform problem, but, as the operant group demonstrated, can learn via shaping to do so. Interestingly, recent work shows that crows, given the experience of pushing down a platform with their beak to obtain food, then dropped a stone onto the platform when it was out of reach [23]. In this study, birds first acted directly on an object, by pushing a platform with their beak. When the platform became out of reach, they then used a tool to extend their ability to act on the platform, by dropping a stone onto the platform. In the present study, the birds also played a role in *initiating* a causal interaction, but the causal interaction itself was between two external objects (the block and platform), rather than between beak and platform, and thus did not involve the bird's own action or body. The bird was therefore required to *observe* the causal interaction rather than to participate in it. These differences between the results here and those of von Bayern *et al.* show that New Caledonian crows can use causal information produced via their own direct action to produce new behaviours to solve a problem, but seem unable to use observation of an interaction between two external objects in a similar context. Further testing is required to examine the role of proprioceptive feedback during such problem solving, and, more generally, if this difference between experienced interactions and observed interactions holds for other behaviours and stimuli.

These results shed light on the evolution of the ability to intervene causally. New Caledonian crows are capable of a

number of complex tool behaviours, such as tool manufacture [13], metatool use (the use of one tool on another) [20] and context-dependent tool use [19,21]. No differences have been found between adults and juveniles at tasks requiring these tool behaviours, or tasks requiring complex causal understanding [18,25,26]. Based on this pattern of results, we would expect, *a priori*, both adult and juvenile New Caledonian crows to create causal interventions. The fact, that all five crows in the intervention group failed, despite observing the causal interaction 10 times more than the children that were tested, suggests that these tool behaviours are insufficient for the evolution of the ability to create novel causal interventions. However, further testing with other behaviours and larger samples of New Caledonian crows are required to confirm this result.

The current findings also suggest that the ability to create interventions can be dissociated cognitively and evolutionarily from other types of causal understanding. New Caledonian crows have demonstrated an abstract understanding of object-object interactions [25,27] and the ability to reason about hidden causal agents [26,28,29]. Interestingly, both this species [18,30] and Eurasian jays (*Garrulus glandarius*) [31] actually outperform children up to the age of seven [32] on certain object discrimination tests of physical cognition using the Aesop's fable paradigm, such as choosing between sinking and floating (or hollow and solid) objects. However, unlike the jays [31], children can solve the 'U-tube' task [32]. This requires the same action-reward relationship (and therefore is just as easy to learn through perceptual motor feedback [33] and operant conditioning) but provides causally counter-intuitive cues, as dropping a stone into a water-filled tube leads the water level in an apparently disconnected tube to rise [32]. Taken together, the pattern of performance seen in these past studies, coupled with the findings presented here, strongly suggest that causal understanding is not based on a single monolithic, domain-general cognitive mechanism. Given that corvids can outperform children up to 7 years old on some tasks, but fail at other tasks that 24-month-old human infants succeed at, it seems highly likely that a number of different cognitive mechanisms contribute to the causal understanding of both corvids and humans. However, it is unclear at present how many cognitive mechanisms are involved, how each of these mechanisms operates, and how they evolve.

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