INNOVATIVE TOOL-MODIFICATIONS AND TOOL SELECTIVITY IN NEW CALEDONIAN CROWS (CORVUS MONEDULOIDES)

Jessica Alfredsson

Supervisors: Linus Holm, PhD
Department of psychology
Umeå University
Sweden

Auguste von Bayern, PhD
Behavioural ecology research group
University of Oxford
United Kingdom
Innovative tool-modifications and tool selectivity in New Caledonian crows (*Corvus moneduloides*)

Jessica Alfredsson

Tool-use and tool-manufacture are thought to require high cognitive skills and have been considered as an exclusive attribute to primates. Recent observations of New Caledonian crows (NCCs) challenge this assumption. In this study 13 NCCs were tested with two different tool production tasks. The NCC either had to straighten a hook or bend a stick to retrieve food from two different kinds of tree trunks. The result showed that 3/5 birds bent sticks and used them to retrieve food and 1/5 birds straightened hooks to retrieve food. The birds managed to solve both tasks but not the birds in the control group. This indicates that NCC's tool making is a flexible innovative act and not just an innate predisposition to bend flexible material. This finding is interesting given that recent studies on human children show that below 8 years of age children fail in similar innovative tool making tasks.

Observations of tool-use and tool manufacture in animals have received much attention because they are exceedingly rare (vanSchaik, Deaner & Merrill, 1999). When tool-use in animals was first reported in the Gombe chimpanzees (*Pan troglodytes*) in the 1960s by Jane Goodall, this was a big revelation (van Lawick-Goodall, 1968) and disproved tool use as a defining ability of mankind (Gibson & Ingold, 1993). Tool use is thought to have played an important role in the evolution of the human brain, intelligence and language (Ambrose, 2001; Byrne, 1997; Cutting, Apperly & Beck, 2011; Fullola i Pericot & Serrallonga, 2000). The emergence of the first primitive stone tools in hominids to the appearance of more sophisticated manufactured tools marks a period of great increase of brain size and, supposedly, intelligence in our ancestors (Reader & Laland, 2002; vanSchaik et al., 1999; Stout, Passingham, Frith, Apel & Chaminade, 2011; Susman, 1994). It has led to the hypothesis that tool use in our ancestors gradually selected for improved cognitive abilities in the physical domain. Yet, an equally possible hypothesis is that a high general cognitive ability was a prerequisite for tool use to arise, i.e. that our ancestors had become cleverer and that is why they suddenly were able to use tools. Hence, the question of whether it was the use of tools that gradually led to higher cognitive competences (domain-specific adaptation) or the development of higher cognitive functions that secondarily gave rise to the ability to use tools (domain-general intelligence) is still open (Kacelnik, 2009). Since we cannot go back in time to observe the brain evolution and tool use behaviour of our ancestors, studying other tool-using animal species that have been exposed to similar or different selection pressures, remains the only available window. This might allow us some glimpses into the evolution of technical or domain-general cognition in relation to tool-use and resolve the question above.
There is an ongoing debate about the definition of tool-use and tool-manufacture and the most recent definition put forward by Shumaker, Walkup and Beck (2011) suggests the following:

The external employment of an unattached or manipulable attached environmental object to alter more efficiently form, position, or condition of another object, another organism, or the user itself, when the user holds and directly manipulates the tool during or prior to use and is responsible for the proper and effective orientation of the tool (Shumaker et al., 2011, p. 5).

Tool manufacture is defined as “any structural modification of an object or an existing tool so that the object serves, or serves more effectively, as a tool” (Schumaker et al., 2011, p. 11).

Tool manufacture in animals is rare and mostly primitive except for the tools made by apes. Not surprisingly apes have been the focus of attention and are ascribed as having the most versatile and complex tool-related cognitive abilities in non-human animals. However, recent observations of New Caledonian crows have challenged this assumption (Weir, Chappell & Kacelnik, 2002). New Caledonian crows (*Corvus moneduloides*) (see figure 1), hereafter referred to as NCCs, are, together with the Galapagos woodpecker finches (*Cactospiza pallida*) (Tebbich, & Bshary, 2004; Tebbich, Taborsky, Fessl & Blomqvist, 2001), the only known bird species that use stick tools for extractive foraging purposes habitually in the wild (Hunt, 1996, Weir, Chappell & Kacelnik, 2002; Kenward, Weir, Rutz & Kacelnik, 2005). Yet, in contrast to the Galapagos finches, NCC’s use and manufacture a wide range of different tools used for different purposes, including the most complex tool manufactured by non-human animals (Kenward, Rutz, Weir & Kacelnik, 2006).

Manufacturing simple tools is something that is difficult even for human children. In Beck, Apperly, Chappell, Guthrie & Cutting (2011) children of different ages were tested to see if they choose appropriately straight or a bent pipe cleanser in order to retrieve a sticker from the bottom of a bucket. The result showed that children between 4- to 7-years were significantly more likely than chance to select the bent pipe cleanser but children between 3 and 4 years did not perform above chance. In a second test, the children were faced with the same task but in this case they only received material for making the hook. The result indicated that few 3- to 5-year olds innovatively created a hook tool and that success with the task gradually increased from 5 to 10 years. It was not until the age of 8 that the majority of children succeeded at the task (Beck et al., 2011).

Interestingly, NCCs are also reported to have one of the largest avian brains in relation to their body size. Additionally, the relative growth of the multimodal forebrain system, i.e. the associative and motor-related structures in the forebrain, is enlarged indicating that NCCs evolved increased technical and general problem-
solving skills compared to other corvids (Mehlhorn, Hunt, Gray, Rehkämper & Günthürkün, 2010). This is remarkable because the forebrain in the corvid family is generally enlarged compared to other bird species and is considered as analogous to the expanded mammalian frontal cortex (Emery & Clayton, 2004). New Caledonian crows belong to the corvid family which is generally large-brained. When corrected for brain to body mass ratio their brain sizes can be compared with those of apes. Furthermore, corvids are known for their advanced cognitive skills, which parallel those of apes in several cognitive studies (Emery, Seed, von Bayern & Clayton, 2007, Seed, Emery & Clayton, 2009). This has led to the proposition that corvids and apes underwent convergent evolution of intelligence (Emery & Clayton, 2004; Seed et al., 2009). Even if they demonstrate similarities in their behaviour the brain structure differ between the species; ape neocortex has a laminar arrangement and the avian pallium has a nuclear arrangement (Emery & Clayton, 2004). There is experimental evidence today that corvids exhibit aspects of a theory of mind, i.e. they can take the visual perspective of conspecifics, respond to their knowledge states (for review see Clayton, Dally & Emery, 2007) and use referential gestures (Pika & Bugnyar 2011). They also possess an episodic-like memory (Clayton & Dickinson, 1998) and appear to be able to plan for the future (Raby, Alexis, Dickinson, & Clayton, 2007; Cheke & Clayton, 2011), but most noteworthy for the purpose of this study are observations of spontaneous tool-use to solve novel problems in experimental settings (Bird & Emery, 2009a, b). This fact renders NCC’s, as the only natural tool-using corvid. Does their cognitive ability also extend to manufacturing of tools to solve problems?

NCCs live in the archipelago of New Caledonia located east of the Australian mainland in the South Pacific Ocean (Bluff, Weir, Rutz, Wimpenny & Kacelnik, 2007). NCCs form stable long-term, maybe even lifelong pair bonds and their group size varies from pairs up to 30 birds but the groups appear to be subdivided into families (Bluff et al., 2007).

![Figure 1. New Caledonian crows.](image-url)
NCCs use tools mostly for recovering large insects such as wood-boring larvae found deep in decomposing wood or to reach smaller insects located under bark etc. A recent study has shown that they acquire a substantial part of their protein and lipid intake by their stick-tool-use (Rutz et al., 2010). In addition to larvae and insects their diet consists of nuts, fruits, seeds, flowers and also other bird's eggs, i.e. they are omnivorous (Bluff et al., 2007).

The first scientific report of tool-use in NCCs by Orenstein was published in 1972, but it was not until 1996, that the complexity and variety of the tool use in NCC’s was described by Gavin Hunt (Hunt, 1996). Hunt reported observations of NCCs manufacturing and completing hooked-twig tools made from branches and leaves. Today it is known that NCCs manufacture and use multiple forms of tools for multiple purposes to probe for and extract insects including twigs, gras-stems, hooked tools or three-stepped cut-outs from barbed Pandanus leaves (tools made by materials from palm-like plants) (Shumaker, Walkup & Beck, 2011). The latter represent the most complex tools manufactured in the animal kingdom as several complex steps are necessary to produce it (Hunt, 1996). Material for the different tools seems to be selected carefully by the bird and NCCs have also been observed carrying tools with them between foraging stops (Shumaker, Walkup & Beck, 2011). According to observations the birds hold the tools at the distal end, insert it in dead wood and then move the tool rapidly back and forth so that the tool catches a prey (Shumaker, Walkup & Beck, 2011). The fishing technique that is used by the NCCs to contract larvae from dead wood requires a remarkable level of sensori-motor control, a technique that is even difficult to master for humans (Rutz & St Clair, 2012).

As a result of their exceptional tool use and manufacture behaviour and their large brain size, NCCs have become the model species for studying cognitive adaptations to tool use. Several studies have investigated whether their tool use behaviour is underpinned by high technical or general cognitive abilities. A strong indicator for higher cognitive abilities related to tool use, would be flexibility in their tool use behaviour and sensitivity to the functional properties of tools. This has for example been tested by exposing NCCs to experimental situations in which they have to select the appropriate tool for a given task (Chappell & Kacelnik, 2002). Chappell and Kacelnik (2002), for example, tested the ability of two captive NCCs to choose stick tools that would be suitable to fish out food placed in a horizontal transparent pipe at different distances. Both NCCs selected tools of appropriate length significantly above chance. Other studies have investigated whether they also choose tools according to other functional properties (Weir, Chappell & Kacelnik, 2002), whether they can use novel tools innovatively (von Bayern, Heathcote, Rutz & Kacelnik, 2009), whether they can use tools for different purposes (Taylor, Hunt, Holzhaider & Gray, 2007) or in appropriate sequence (Wimpenny, Weir, Clayton, Rutz, & Kacelnik, 2009). Tool production by NCCs in contrast has not been addressed by many experimental studies, except for Weir et al.'s (2002) study...
referred to below. But observational studies in the wild suggest that NCCs may exhibit sensitivity to the functional properties of their tools when producing them. For example, when creating a hook tool out of a twig, they snap off the branch below the junction where the wood is strongest, which ensured that the hook was positioned at the end of the tool (Hunt and Gray 2003). They also removed side twigs from the tool twig by snapping them off near their bases instead of pulling them off and in that way the tool became more efficient (Hunt 1996; Hunt & Grey, 2003). Alternatively NCCs are not sensitive to functional properties of material around them but instead just display an unusually strong inherited motivation to interact with and combine objects which in turn produces tool use (Rutz & St Clair, 2012).

The objective of this study was to test whether NCC’s can modify tools innovatively and flexibly depending on the functional properties of the tools and the requirements of the task. Apart from Beck et al.’s paper (2011), the present study was inspired by Weir et al.’s paper (2002), reporting the first case of innovative tool making in non-primates, by the now world-famous NCC "Betty". Deprived of an adequate hooked tool, Betty spontaneously created a hook by bending a metal wire, so that she could lift a small bucket up from a vertical tube containing food (Weir, Chappell & Kacelnik, 2002). In order to examine whether this unique behaviour was a truly flexible innovative act rather than an innate predisposition to bend flexible plant material by 'genetic default' and without any functional understanding, two aspects deserve further investigation. First, the study ought to be repeated with a larger number of subjects with controlled pre-experience of the task affordance. Second, in order to examine the flexibility and innovativeness of the behaviour, it ought to be revealed whether the NCCs would also unbend a hook into a straight tool if necessitated by the task. The experiment consisted of two problem-solving tasks that required the use of a hooked or a straight tool respectively. The crows first experienced a training phase in which they either (1) learned to select the correctly shaped tool for the task or (2) learned about the behaviour afforded by the task ("push" or "pull") with pre-inserted tools. Subsequently, they were tested in a situation, in which only tools of the wrong shape was available but that were modifiable.

If the crows are sensitive to the functional aspects of the tool and have problem solving abilities the prediction would be that the NCC’s would adapt the tools to solve the task within the first session. Also, if the NCC’s managed to solve the task they would continue with the successful behaviour in the subsequent sessions. If, on the other hand, the crows were learning to modify tools by chance, the prediction would be that the NCC’s would gradually improve by individual learning and reinforcement of the used technique. They would develop their skill over several trials and the outcome would be a learning curve in which they gradually improved their technique. If they had innate predispositions for bending tools, it
would be expected that they would be more successful in the bending task than in the unbending task and succeed immediately - also in the control group.

Method

Subjects
Subjects were 13 captive New Caledonian crows (Corvus moneludoides) consisting of seven females and six males. Except for one hand-raised female, the NCCs were wild caught in New Caledonia in 2003 or 2009. Four subjects were sexually immature (about three years old), five were about four years old (young adults), the hand-raised individual was 7 years old and the remaining three birds were adults of unknown age.

All birds were either kept in pairs or in family groups (parents with their young) in outdoor aviaries (ca 15m²-32m²) with free access to adjacent lit (special sunlight imitating bird lamps) and heated indoor houses (ca 7m²). The birds were maintained at a 12:12 photoperiodic light-dark cycle and had ad libitum access to water and food throughout the day. During night they were kept in their indoor facilities, where heat-lamps, food and water were provided. Their maintenance diet consisted of a special freshly prepared mixture (minced beef, curd, rice or whole-wheat pasta, minerals and vitamin supplements, dried insect mixture, boiled yolk, high quality seed oils etc), soaked cat-biscuits, fruit and cereals, seeds and raisins. They also regularly received eggs, yogurt, seeds and nuts and Nutribird® pearls. The diet was occasionally supplemented with other available food types such as deer meat, bones, chicken and wild berries.

The aviaries were enriched with fresh branches with leaves, foraging squares with pebbles and wood-bark, planted trees and grass as well as bathing water. The birds were supplied with twigs, plant material, stones and other toys. The aviaries were kept hygienically clean and the indoor aviary floor was covered with clean newspaper.

Habituation
Prior to the training phase the birds were habituated to the tree trunks and experimental compartments. After having learnt about baited pistachio nuts (see below) each test bird received six habituation sessions (about 10 min each) in the experimental compartment. Each session was preceded by 45 min food deprivation. The transparent door was removed from the trunks with three pieces of meat and three worms inside the cavity/the tunnel(s) and also six filled pistachios on top of the tree trunk (for the pull condition) or under the tree trunk (for the push condition). After this habituation the birds had four more habituation sessions with the same settings but now with 3 filled pistachios and 3 pieces of
meat inside the cavity/the tunnel(s). The birds were also habituated to the test person with daily contact for one month before the training started.

**Experimental Apparatuses**

**Tree-trunks**

Two different experimental apparatuses, consisting of chunks of horizontally cut wooden logs with natural bark, were used. These ‘tree trunks’ were chosen in order to create a naturalistic experimental setting for the birds, because wild NCCs are known to obtain a substantial proportion of their diet by foraging on branches, logs and decomposing tree trunks for beetle larvae. The first log had a large central cavity and was labeled ‘pull-trunk’ because *hook tools* were required to pull up food through a single hole in the surface covering the cavity (see Figure 2). The second log featured a surface with three holes that were connected to three narrow tunnels (see Figure 2) and was referred to as ‘push-trunk’, because *stick tools* had to be inserted into the holes to push food out of the channels.

![Figure 2](image) **Figure 2.** (A) The setup for the tool selection training pull group (with the right tool inserted) with the square frame next to it together with 6 sticks and 5 hooks (1 pre-inserted) in a randomized order. (B) The setup for the tool selection training push group (with the right tool inserted) with the square frame next to it together with 5 sticks (1 pre-inserted) and 6 hooks in a randomized order.
**Training tools**

As already indicated a different type of tool was required for each tree-trunk, namely a stick tool with hooked ends for the ‘pull-trunk’ and a straight stick tool for the ‘push-trunk’. For the tool selection groups both tool types were made from ca 20 cm long bamboo sticks and the hook tools had pieces of metallic wire at both ends (1 mm in diameter, double folded and twisted with the ends inserted in the bamboo stick to avoid sharp edges). During the training phase (described below) these ends were stabilized with black tape (see figure 3) and were ‘fixed’, i.e. could not be modified by the NCCs. These tools were later developed and instead of only having metal wire at the ends the metal wire was covered with green pipe cleaner and dark green tape (see figure 3). For the tool function group the tools were also made from about 20 cm long bamboo sticks and for the pull group the tools had a piece of metal wire at the end shaped in a U so the food piece could be attached to it (see figure 3). The push group had a piece of string attached at the end of the sticks so it could be fixed to the trunk. The tools were later developed (after the first crows started to enter the test phase) from having black tape and metal wire on only one side in to having wire and pipe cleaners attached with dark green tape on both sides (see figure 3). After changing the design of the tools a new training phase started.

**Test tools**

In the experimental phase the tool ends were made from bendable metal wire (0.8 mm in diameter covered with green plastic with the end bend to avoid sharp edges) with green pipe cleaners wrapped around secured with dark green tape (see Figure 3). These tools were ‘modifiable’, i.e. could be bent or unbent by the NCCs. The straight tools had ends of about 3 cm length each (see Figure 3). The hooked tools had ends of about 3 cm, and were bent at 90° angle from the stick. The hook tools were initially slightly U-shaped; the shape was later (after a few crows had entered the test phase) straightened at 90° (see figure 3).

![Figure 3](image)

*Figure 3.* (A) The first type of non-modifiable tools for the tool selection training. (B) The second type of non-modifiable tools for the tool selection training. (C) The modifiable test tools. The hooked tool is bent in 90° to the left and as a u-shape to the right. (D1/D2) The tools used for the tool function pull condition during training. (E) The tools used for the tool function push condition during training.
**Food reward**

The food reward consisted of one giant meal worm (*Zophobas morio*) and one piece of beef heart packed together in between two empty pistachio shells, which were sealed with some transparent Tesa® cling film (see figure 4). Each tree trunk was baited with three such filled pistachios.

![Image of food reward](image)

*Figure 4. The food reward.*

**Experimental Groups**

The subjects were divided into three experimental groups (see figure 5), each of which went through a different training regime prior to the actual tests. Eight birds were assigned to the (a) 'Tool-Selection-Group', which was trained to select correct tools out of a set of six correct and six incorrect tools and use them to obtain food from the respective tree-trunk (see figure 2). Three birds were assigned to the (b) 'Tool-Function-Group', which received training on either (i) pulling up food attached to three hooked tools pre-inserted in the central hole of the pull-trunk or (ii) obtaining food by pushing down three tools pre-inserted in the three holes of the push-trunk. The third (c) 'Control Group' comprised two birds which received no training related to tools. One of them obtained 3 food pieces offered on top of the pull-trunk whilst the other obtained 3 food pieces presented under the 3 channels of the push-trunk.

Birds from the tool function and the control group continued with tool selection training and subsequent tests. Birds that did not interact with the tools after motivation help (pre inserted tools with food pieces next to them) were excluded from further testing (see figure 5 for more details).
<table>
<thead>
<tr>
<th>Bird</th>
<th>Training</th>
<th>Test</th>
<th>Training</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annie-Claude</td>
<td>TS Pull</td>
<td>Modify tools</td>
<td>TS Pull</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Barney</td>
<td>TS Pull</td>
<td>Modify tools</td>
<td>TS Pull</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Mango</td>
<td>TS Pull</td>
<td>Modify tools</td>
<td>TS Pull</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Liane</td>
<td>TS Pull</td>
<td>Modify tools</td>
<td>TS Pull</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Uék</td>
<td>TS Push</td>
<td>Modify tools</td>
<td>TS Push</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Jungle</td>
<td>TS Push</td>
<td>Modify tools</td>
<td>TS Push</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Tortue</td>
<td>TS Push</td>
<td>Modify tools</td>
<td>TS Push</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Papaye</td>
<td>TS Push</td>
<td>Modify tools</td>
<td>TS Push</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Tabou</td>
<td>TS Pull</td>
<td>Modify tools</td>
<td>TS Pull</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Kukui</td>
<td>TS Push</td>
<td>Modify tools</td>
<td>TS Push</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Tumulte</td>
<td>TS Push</td>
<td>Modify tools</td>
<td>TS Push</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Aigaios</td>
<td>C Pull</td>
<td>Modify tools</td>
<td>TS Pull</td>
<td>Modify tools</td>
</tr>
<tr>
<td>Coquille</td>
<td>C Push</td>
<td>Modify tools</td>
<td>TS Pull</td>
<td>Modify tools</td>
</tr>
</tbody>
</table>

**Figure 5.** Overview of the NCCs division into the different groups and their different tasks.

**Experimental Setup**

The tree-trunks were set up on the floor or on a table in a partition (2.5 m x 1.50 m x 2 m) of the indoor aviary with their back sides close to a wall. The indoor compartment contained several perches at approximately 1.50 m height and was lit by fluorescent zero flicker lamps covering the natural daylight spectrum (Arcadia®). The compartment was carefully screened for alternative tools carried in by the NCCs prior to each training or test. At ca 30 cm distance from the tree-trunk a low wooden 30 cm x 30 cm frame was set up containing the tools. A camera (Sony Handycam DCR-SX65) was set up on the opposite wall covering the area around the tree trunk and the wooden frame with the tools.
Experimental Procedure

After 45-60 min of food-deprivation the subjects were allowed into the experimental compartment. Training and testing took place in the birds’ normal indoor aviary but in visual isolation from the social group which was kept out during the 16 min training or 18 min testing time. The birds could however hear their social group during testing and could remain in vocal contact. Both training and testing sessions were videotaped. The birds entered the indoor compartment with the prepared experimental setup. The experimenter switched on the camera, placed out the tools in the wooden frame (or pre-inserted them into the apparatus) and then quickly withdrew from the experimental compartment. The training session consisted of two 8 min trials and test sessions consisted of two 9 min trials (allowing the birds to have more time modifying the tools). During the 8 or 9 min phases the bird had the opportunity to retrieve three filled pistachios from the tree trunk. When the first 8 or 9 min had passed the experimenter entered, re-baited the apparatus (or pretended to re-bait in case the rewards had not been taken) and placed the tools back to order. Then the birds received another 8 min training trial or 9 min test trial. Hence, the bird could retrieve a total of 6 rewards during the 16 min (+ baiting time) or 18 min (+ baiting time) of a training or test session. The food deprivation was subsequently continued for another 10 min phase after the sessions so as to keep their motivation up during the training/testing.

The NCCs were tested once or twice a day. One session took place in the morning between 7 am and 11 am and another in the afternoon between 2 pm and 7 pm. Each individual bird had at least 4 hours between the two training or test sessions. The experimental procedures and training criterions of the three experimental groups differed slightly. Once these criterions were reached the birds proceed to the testing stage.

**Tool selection group**

The training sessions were continued until the NCCs reached the following criterion:

(1) they participated in a minimum of 16 sessions (32 trials in total).
(2) within the last ten sessions they had retrieved 30 food pieces.
(3) within the last six sessions not failing to retrieve any food from the tree trunk (within the 16 min session).
(4) within the last six trials the birds did not make any of the following 'mistakes': (i) carried wrong tools around, outside of the frame, (ii) picked up wrong tools after throwing it out from the frame (iii) made insertion attempts with a wrong tool.

**Tool function group and control group**

To reach the criterion, the birds had to retrieve 30 food pieces within the last ten sessions (20 trials in total). Also, the birds should within the last six sessions not have failed to retrieve any food from the tree trunk (within the 16 min session).
Experimental procedure for the test phase

The experimental procedure was identical to the training phase. Each subject received 12 test sessions with a training session interspersed after every three test sessions in order to keep the birds’ motivation up.

Scoring

Tool selection training

In order to assess the speed at which the birds learnt to select only the appropriate tool in the tool selection training phase, videos were scored per trial and session according to (i) how many food pieces the birds retrieved, (ii) how many and what type of mistakes they made (i.e., number of insert attempts of wrong tools, wrong tools picked up and carried around). The total amount of wrong tools that could have been inserted ranged between six and zero i.e. insertion attempts were only counted once if the crow inserted the same wrong tool twice (iii) how many and which type of tool was found inserted in the tree trunk.

Test

For each trial and session the following scoring was carried out; (i) identification of how many and to what extent the tools were modified by the crows (i.e. angle modification from original shape) (ii) the tool modification technique used (‘bending an end directly in the beak or bending by forcefully pressing or repeatedly pushing down the distal end) (iii) how many food pieces they retrieved with each modified tool.

Ethical questions

The NCCs were tested in purely behavioral tests that were not stressful, but on the contrary stimulating and rewarding. Ethical rules of the Department of Zoology, University of Oxford were followed.

Results

Training phase

The three NCCs in the tool function group (N=3) (two in the push condition (N=2) and one in pull condition (N=1)) reached the criterion of retrieving 30 food pieces within ten subsequent trials within approximately 15 trials. Likewise the two NCCs in the control group (N=2) retrieved the minimum of 30 food pieces within ten trials.

Three NCC’s of the tool selection group (see figure 5) had to be excluded for their lack of activity during the training phase. One NCC in tool selection pull condition (Liane) was excluded from the training because of health issues. As seen in figure 6 the number of tools of the wrong type the crows inserted or attempted to insert was higher in the beginning of the training trials and then decreased indicating
that the NCC learned what kind of tool was needed for solving the task. The amount of wrong tools is higher in the pull-trunk condition than in the push-trunk condition. The birds needed different amount of training trials to reach the criterion and the mean number is based on the trials where all the birds were attending (16 sessions for push condition and 24 sessions for pull condition, for more details about the total amount of training trials needed for reaching the criterion see Appendix).

**Figure 6.** (A) Mean number of the insertion attempts of the wrong selected tools for push condition ($N=3$) across the training trials. (B) Mean number of the insertion attempts of the wrong selected tools for pull condition ($N=4$) across the training trials.

**Test phase**
Four NCCs in the tool selection group successfully created functional tools by modifying a non-functional ‘wrong’ tool during the test. Three out of four subjects in the pull-condition bent hooked tools with which they succeeded to retrieve food from the pull-trunk (the forth bird did some modifications with the distal technique but did not retrieve any food pieces); one out of three birds in the push-condition unbent a straight tool and successfully retrieve food from the push-trunk (the other two birds did modifications with distal technique and beak in combination with distal technique respectively in their first trial but did not retrieve any food pieces). No clear pattern of age or gender became apparent (see Table 3). In contrast, none of the NCCs in the tool function group or in the control group made successful modifications (although two of them that did some modifications, see table 3).
Table 3. Overview of the tested NCCs detailing test group, name, sex and age class, the style of the modifications and in which session the first successful modification happened. The technique used for the successful modification is divided into Distal = Distal-end-bending; Beak = Beak bending (see description below).

<table>
<thead>
<tr>
<th>Group</th>
<th>Name</th>
<th>Gender</th>
<th>Age Class</th>
<th>Style</th>
<th>1st successful session</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS Pull</td>
<td>Annie Claude</td>
<td>Female</td>
<td>Adult</td>
<td>Distal</td>
<td>-</td>
</tr>
<tr>
<td>TS Pull</td>
<td>Barney</td>
<td>Male</td>
<td>Adult</td>
<td>Distal</td>
<td>3</td>
</tr>
<tr>
<td>TS Pull</td>
<td>Mango</td>
<td>Male</td>
<td>Young adult</td>
<td>Distal</td>
<td>1</td>
</tr>
<tr>
<td>TS Pull</td>
<td>Aigaios</td>
<td>Male</td>
<td>Young adult</td>
<td>Beak</td>
<td>1</td>
</tr>
<tr>
<td>TS Push</td>
<td>Uék</td>
<td>Female</td>
<td>Adult</td>
<td>Beak/Distal</td>
<td>6</td>
</tr>
<tr>
<td>TS Push</td>
<td>Jungle</td>
<td>Male</td>
<td>Immature</td>
<td>Distal</td>
<td>-</td>
</tr>
<tr>
<td>TS Push</td>
<td>Tortue</td>
<td>Female</td>
<td>Young adult</td>
<td>Beak/Distal</td>
<td>-</td>
</tr>
<tr>
<td>TF Push</td>
<td>Tabou</td>
<td>Male</td>
<td>Immature</td>
<td>Beak/Distal</td>
<td>-</td>
</tr>
<tr>
<td>TF Push</td>
<td>Kukui</td>
<td>Male</td>
<td>Immature</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TF Push</td>
<td>Tumulte</td>
<td>Female</td>
<td>Immature</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Control Push</td>
<td>Coquille</td>
<td>Male</td>
<td>Young adult</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Control Pull</td>
<td>Aigaios</td>
<td>Male</td>
<td>Young adult</td>
<td>Distal</td>
<td>-</td>
</tr>
</tbody>
</table>

During the scoring of the videos two tool modification techniques were distinguished. In the first technique the crow used its beak to bend or straighten a non-functional tool (*beak technique*). This could be done by inserting the tool in the central cavity, thus keeping it stable and then bending the end that pointed upwards from the trunk with the beak. Alternatively, the crow would stand on the tool and then grab one end of the tool with the beak to modify the tool. In the other technique the crow inserted the tool in the trunk and then (repeatedly) pushed it against the bottom of the trunk so that the distal end was bent, resulting in a hook (*distal technique*). This also occurred for the push-tree-trunk group where the end of the hook were inserted and then manipulated inside of the trunk until it was straight enough to go down into the tunnel. The two different techniques tended to result in two different shapes; the hook was mostly shaped into a u-shape when it was bend with the beak whilst it was more straight when it was created inside of the trunk (see figure 7).
Figure 7. The two different modifications styles. (A) Angle of the hook modified by bending it with the beak. (B) Angle of the hook modified by pushing it against the inside of the tree trunk.

**Barney**

The angles of Barney’s successfully bent hooks remain stable over the trials from the beginning of the tests averaging at around 80°.

![Graph showing successful modifications and their deviations from 180° over time for Barney (pull-condition).](image)

**Figure 8.** Successful (i.e. retrieved food) hook modifications and their deviations from 180° over time for Barney (pull-condition).

Barney first succeeded to retrieve food with a modified tool in his third test trial bending it to ca 80° (see figure 9) and retrieved one piece of food. He was successful in 14 out of the remaining 18 trials. The following seven modifications that he used after the first successful modification were all successful (see figure 9). Barney’s bending technique was the distal-end-bending one, in which the tool end inserted into the trunk was pushed against the bottom of the cavity.
Figure 9. An overview of the first eight used tool modifications for Barney in the pull condition. The first picture shows the first successful modification (third test trial) where Barney retrieved one food piece. The following seven were all successful.

**Mango**

The angle of Mango’s successful modified hooks increases over the trials (see figure 10).

![Figure 10](image)

**Figure 10.** Successful (i.e. retrieved food) hook modifications and their angles over time for Mango in the pull condition. The angle of the successful hooks increased over time.

Mango did his first successful modification (bent to approximately 55°) during his first test trial (see figure 11) and retrieved one piece of food. He was successful in eight out of the remaining 23 trials. The subsequent seven modifications he used after the first successful modification can be seen in figure 11. All of the tool modifications were successful except for two (see figure 11 for more details). Mango used the distal-end-bending-technique to modify the tools.
Figure 11. An overview for the first eight used tool modifications for Mango in the pull-condition. The first picture shows the first successful modification (first test trial) where Mango retrieved one piece of food. The following seven were all successful except for number three (bent it in the end of the trial not having time to retrieve any food pieces) and number four.

Aigaios

Aigaios' development over time in his successfully modified hooks and their angles can be seen in figure 12. The angle of the successful hooks started out at 40°, remained mostly above 70° to 90° from trial 5 onwards and became more stable towards the end.

Figure 12. Successful (i.e. retrieved food) hook modifications and their deviations from 180° over time for Aigaios (pull condition).

Aigaios succeeded the first time in session 1, trial 1 (see figure 13) with a tool bent to ca 45° and retrieved one piece of food. He was successful in 21 trials out of the remaining 23 trials. The following seven modifications that were used, i.e. which were inserted in the cavity, were all successful (see figure 13). Aigaios always bent...
the hooks with the beak. Aigaios took a stick, put it into the tree trunk, grabbed the other end of the tool with the beak and turned it down resulting in a hook. After bending the stick Aigaios turned the tool around and inserted the hooked end in the tree trunk and retrieved food pieces by fishing them up.

**Figure 13.** An overview of the first eight tool modifications that were used, i.e., inserted, for Aigaios in the pull-condition. The first picture shows the first successful modification (first test trial) where Aigaios retrieved one piece of food. The following seven were all successful.

The most sufficient angle for the hook for all three successful birds seems to be approximately between 60° and 90° (see figure 14).

**Figure 14.** The amount of food pieces retrieved according to the angle of the tools for all successful subjects in the tool selection pull group (N=3).

The amount of retrieved rewards increased across test sessions for all the successful birds in the tool selection pull condition (see figure 15).
**Figure 15.** The amount of retrieved rewards over the test sessions for the tool selection pull group (Barney, Aigaios and Mango).

**Uék**

The amount of retrieved rewards was increased over the test sessions for the successful bird (Uék) in tool selection push condition (see figure 16).

**Figure 16.** The amount of retrieved rewards over the test sessions for the tool selection pull group (Uék).

Uék did her first successful modification during her fifth test session (see figure 17) and retrieved one piece of food. After the first successful unbending with the beak-technique she had a success gap of 3 trials and then after starting to use the distal-technique she was successful in 10 trials out of the remaining 11 trials. The following seven modifications that were used can be seen in figure 17 and all of them were successful. Uék used two different modification techniques. In her first successful session (session 5, trial 2) she unbent the hook with her beak by standing on the tool and several times nibbling the modifiable end until it was straight enough to be inserted. In the following trials she used the other technique that consisted of inserting the tip of one non-functional i.e. 90° end holding it in the beak near the inserted end or near the middle part of the bamboo in one of the
three openings on top of the tree trunk and manipulating the tool by holding the tool at the end of the bamboo, until it was straightened enough to be pushed down in the tunnels.

Figure 17. An overview of the first eight tool modifications Uék used in the push condition. The first picture shows the first successful modification (fifth test session, trial two) where Uék retrieved two food pieces. The following seven were all successful.

Uék was the only NCC in the push condition (N=4) that achieved to unbend a hook. Figure 18 shows the amount of food pieces retrieved by the modified tools and their respective angles.

Figure 16. The amount of food pieces retrieved according to the angle of the tools for the successful subject in the push condition (N=1).

Discussion

Four NCCs managed to produce tools, innovatively by converting non-functional material into functional devices. This indicates that they have flexible innovative behaviours and that high level cognition can evolve in different brain structures.
After the training phase in which the NCCs learned to select appropriate tools and subsequently use them, three out of four NCCs were tested with only non-functional tools. They succeeded to straight sticks into functional hooks, with which they retrieved food. Additionally, one out of three crows solved the complementary, arguably more difficult task of shaping a hooked tool into a straight one. This has never been shown in non-human animals to date. So far two studies report the bending of straight tools into hooked tools for pulling up a bucket with food from a transparent vertical tube. In a previous study on NCCs, the female Betty, deprived of functional hooked tools, spontaneously bent a straight wire into a hook and retrieved the bucket (Weir et al. 2002). A subsequent study on naturally non-tool using rooks (Corvus frugilegus) reports similar behaviour (Bird & Emery, 2009a). Both species had previously used hooked tools like the crows in this study. It was not clear whether the initial hooks resulted from accidental actions (trying to use a straight tool to fish the bucket out of the tube) that were successively improved through shaping and reinforcement. Alternatively, it could not be excluded that the birds are genetically predisposed to bend flexible material. NCCs use hooked tools for foraging; rooks build fairly complex nests high up in the canopy and may be required to bend flexible branches in order to interweave the twigs and form the nest.

Two studies on children found that only at the age of 8 years did children consistently make tools in a similar problem situation, even though children are proficient tool users from an early age (Beck et al. 2011). This suggests that making tools to solve a task is cognitively demanding. A follow up study by Cutting et al. (2011) investigated more closely the reason why this may be. They repeated the study and found that the innovative part of tool making, i.e. the physical transformation of unsuitable tools into suitable ones, is an ‘ill-structured problem’ in psychological terms. An ill-structured problem is difficult and demanding since the solver has to derive and hold in mind the solution to the problem, inhibit irrelevant actions, and plan a sequence of actions to achieve the goal (Cutting et al., 2011). According to Cutting et al. (2011) innovative tool-making can be divided into two different aspects. The first aspect is the physical transformation of materials and the other aspect is the tool innovation aspect. This is the prior step of mentally representing the type of tool suitable for the task (Beck, Apperly, Chappell, Guthrie and Cutting, 2011; Cutting, Apperly, & Beck, 2011). Given the previous tool use training our birds had seen and used functional tools before, so according to Cutting et al.’s definition, they did not make innovative tools. On the other hand, one can still argue that their tool making was an innovative behaviour, because they had never been required to or reinforced to make tools in experimental situations.

Two birds in the control group (one with pull condition and one with push condition) and three birds in the tool function group (two with push condition and one with pull condition) were tested but they were all unsuccessful to modify
useful tools. The control group was tested in order to examine whether NCCs could solve the task without being familiar with the shape of the tool nor their functional properties. Hence, the control condition incorporated Cutting et al.’s (2011) tool innovation aspect. A sample size of two subjects is of course insufficient and should be regarded as a pilot attempt. However, the fact that one of those control birds, Aigaios (pull condition), did modify tools quite readily yet without succeeding to solve the task, indicates that this possibility should not be ruled out. More birds should be tested in the control condition. The purpose of the tool function group was to test whether experiencing just the function but not the shape like in the tool selection group (i.e. learning about the shape while selecting and choosing it) would suffice for the birds to create functional tools when functional pre-inserted tools were not available. This would seem less demanding than the control condition. In the tool function condition the birds would know what the function of the tool (pull up or push down) would be. Also in the tool function group one bird out of three modified tools. Tabou created a fully functional hook in the end of one trial, but never used it in time.

In the tool selection group seven out of eleven birds reached the criterion. As seen in figure 6 the amount of erroneously inserted tools is decreasing over the trials – their selection of tools adapted to the task. Out of these seven birds four managed to successfully modify the tools in the test, three in the pull group and one in the push group. According to the predictions; if the bending but not the unbending behaviour was innate, the majority of crows should have solved the bending task from first trial (in all experimental groups). Also, no crow should have succeeded in the unbending task. Neither the former nor the latter turned out to be the case. If on the other hand the crows were sensitive to the functional aspects of the tool and have innovative problem solving abilities, the NCC’s would manage to solve both conditions (pull- as well as the push) within the first few sessions. Perhaps a bigger sample size allowing for statistical inferences to NCC population would be required to strictly rule out innateness. Due to time limitations the birds were not tested in both the pull- and push-conditions. On the other hand, when looking at the birds in total they managed to solve both tasks and some of them within the first session. The second prediction was that if the NCC’s managed to solve the task they would continue with the successful behaviour in the subsequent sessions. This was true for one bird out of four that successfully modified the tools. Aigaios, who used the beak technique when modifying the tools, was the only bird to continue in the following trials to modify the tools successfully. The other three birds had a gap after the first successful trial of 3-6 trials. Perhaps the modification technique (see figure 7) gives a clue to why this was the case. Even if both of the techniques were successful, the modification style only used by Aigaios, in which the beak was used, implies that the bird knew what it was doing. It seems not to be due to chance that the modification happened. In contrast, when using the other modification technique (the "distal" technique), the bird manipulated the tools inside of the tree
trunk. The birds might have accidentally turned it into a hook like the rooks mentioned above. Even if the beak technique can arise without an understanding of tool functionality, it is still a sufficient technique for the birds. The hook can be created accidentally at first quite easily and then improved through individual learning. However, they did improve their skills over the trials and managed to retrieve more and more rewards (see figure 9 and 17). This indicates that they got more proficient in their techniques. On the other hand, if the NCCs were learning to modify tools by chance, the prediction would be that the NCC's would gradually improve by individual learning and reinforcement of the used technique. They would develop their skill over several trials and the outcome would be a gradual learning curve in which they gradually improved their technique. Instead, two of the birds started to solve the task within the first session. That is, the two birds displayed knowledge transfer from the training phase. Since the control group did not manage to solve the task, the success of these two NCCs cannot be explained simply by innate predispositions for bending tools.

The NCCs improved their modification style and in that way managed to retrieve more and more food pieces the more trials they had (see figure 9). The most successful angle of the hook seems to be between ca 60-90° (see figure 8). The success rate may also depend on how skilled the bird is when it comes to using the tools. Being able to fish up food pieces with a hook requires control over the actions and fine motor abilities. The personality of the NCC may also play a part in the success rate. If the bird is curious and less neophobic it is more likely to start manipulating the tools earlier and trying them out in different ways. Aigaios and Mango successfully modified the tools in the first test session; Barney managed from the third test session onwards (see figure 9, 11 and 13). According to the success rate over time Barney modified the tools with a high angle from start (see figure 8) meanwhile Aigaios and Mango increased the angle over time (see figure 10 and 12). Worth taken into account is also that the tools that had been photographed and used for the results came from the end of the trials (after the 9 min). It is therefore possible that the modified hooks had a different shape when they were used during the trials. Furthermore, the hooks could have been altered when taken out from of the tree trunk by the bird. The shape of the tools should be seen as an indication of the modification and not as a perfect representation of the tools being used.

Several difficulties that could have impacted on the results were encountered in this pilot study, which could be improved by future studies. For example, the choice of the tools and the visual as well as tactile properties of the modifiable or non-modifiable ends may play a big role. In the first training phase natural bamboo sticks (ca 0,4 cm in diameter) with or without metal hooks were used and were readily taken by the birds during tool selection training. Yet in a later training phase, they were adjusted so they looked more like the tool subsequently used in the test. Green pipe cleaners were added to the un-modifiable ends, in order to
avoid neophobic responses in the test. For the test the tools therefore looked like the tools used during training, but were suddenly modifiable. It might have been better to use tools that looked similar but not identical, so the birds would not consider the tools in the test un-modifiable (perhaps the NCCs had previously learnt that they could not modify them). Also, it is possible that the birds prefer thinner tools, than the ones used in this study, and therefore might have been less motivated. Yet, if the tools had consisted of only thin flexible wire like in the Weir et al. (2002) and Bird & Emery (2009a) study, it would have been more difficult to control whether the birds bend the tools accidentally at first or not. Having the modifiable parts only at the ends required more effort to make a modification. The green pipe cleaner on the wire was used so the tool ends would be more 'bulky', in order to make it easier to fish out the food pieces up from the pull-trunk and to preclude the insertion of bent tools in the push-trunk. Another change that was made in the end of the training phase and for some birds at the beginning of the test phase was the shape of the hooks. The hooks were initially bent in a u-shape but it had to be changed, since it would have been very difficult for the birds to modify such a tool. Therefore, instead of having the hooks shaped as a u-shape they were bent in a straight 90° angle. This simplified the data collection as well since it was easier to detect if there the hooks had been modified. Another possible improvement for future studies may be to alter the layout of the study so that the birds would be trained and tested with both types of tree trunks. Perhaps in the same trial or randomize the tree trunk between the two parts of the trial (e.g. 8 min with the pull tree trunk and then 8 min with the push tree trunk in the same training session). This would give the crows more opportunities to learn about the functionality of the two different types of tools.

It still remains unknown to what extent animals possess a technical intelligence (physical cognition) that allows them to reason about the functionality of their tools when using them or when manufacturing them. But this study provides insight into the NCCs' ability to innovatively create a tool according to need – something that is hard even for human children. Four of the NCCs managed to solve the complete task, first by learning to select the right tool for the task and then later to modify the tools into successful ones. This indicates that they have a high level of tool-use cognition and that high level cognition can evolve in morphologically highly different brain structures. The brain structure does not have to be the one of apes and humans to form and produce complex behaviours. The question that should be asked is how complex cognition can evolve. Is it triggered by the environment or is it something in the specimen that makes it possible? This is a complex question and based on experience, when it comes to complex phenomenon's it is seldom only one single aspect that is involved. The environment in combination of biological diversity and the plasticity of these specimens would be an opening for complex cognition to evolve. Social learning is something that makes the development go faster – instead of saving information in
the DNA over generations the information can travel between individuals during one single lifetime. For future studies it would be of great interest to look at social learning in a tool modification context. Since two different modification styles were discovered during this study social learning could be analyzed. One group could be demonstrated with one style and another group with the other style. If the birds learned from each other socially they would probably be faster in succeeding the task than if they had to learn it by themselves. NCCs examine flexibility in tool making abilities and to see how much they differ from other birds it would be interesting to compare their result with others, for example rooks. NCCs challenged the assumption that tool-use and tool-manufacture is an exclusive attribute to primates – perhaps it is about time to realize that primates are not alone with their skills. They are as special as any other species on this planet since in the end it is all about the ability to adapt to the environment.

Acknowledgements

I want to thank my supervisor Auguste von Bayern making this project possible and also the research team members Berenika Mioduszewska, Clara Domingo and Cordula Weber for all the help and support. I also thank my supervisor Linus Holm for useful comments and support.
References


Appendix

Total amount of training sessions for the individual NCCs in tool selection group

Appendix figure 1. (A) The total amount of training sessions needed for the individual NCC to reach the criterions in the tool selection group pull. (B) The total amount of training sessions needed for the individual NCC to reach the criterions in the tool selection push group.