Flexible tool set transport in Goffin's cockatoos

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Highlights

- Captive Goffin's cockatoos are able to innovate the flexible use of a tool set
- Goffin's can switch flexibly between transporting a tool set or individual tools
- Results suggest the ability to recognize the need for a tool set
- Results suggest a convergence of associative tool use between birds and primates

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In brief

In this study, Osuna-Mascaró et al. test Goffin's cockatoos in tasks inspired by the termite fishing of wild chimpanzees. Goffin's are able to flexibly use and transport a tool set for immediate future use, suggesting the ability to recognize the need for both tools as a set for task success.

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Flexible tool set transport in Goffin's cockatoos

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SUMMARY

The use of tool sets constitutes one of the most elaborate examples of animal technology, and reports of it in nature are limited to chimpanzees and Goffin's cockatoos. Although tool set use in Goffin's was only recently discovered, we know that chimpanzees flexibly transport tool sets, depending on their need. Flexible tool set transport can be considered full evidence for identification of a genuine tool set, as the selection of the second tool is not just a response to the outcomes of the use of the first tool but implies recognizing the need for both tools before using any of them (thus, categorizing both tools together as a tool set). In three controlled experiments, we tested captive Goffin's in tasks inspired by the termite fishing of Goualougo Triangle's chimpanzees. Thereby, we show that some Goffin's can innovate the use and flexibly use and transport a new tool set for immediate future use; therefore, their sequential tool use is more than the sum of its parts.

INTRODUCTION

Tool innovations are a prime repository for the evolution of technology across species. Nevertheless, although rare overall, tool innovations can still occur along a considerable scale of relational and sequential action complexity across animals, with the vast majority of examples being simple, primary, or even self-directed object interactions.[1–3]

The most sophisticated types of animal tool innovations recorded to date are those that involve more than one tool to achieve a single goal (associative tool use).[1] Within associative tool use, complexity arises for a variety of reasons, such as different tools having complementary functions, each tool requiring different movement patterns, a higher total number of spatial relationships to consider, or even a need for sophisticated action planning.[4]

A particularly remarkable form of associative tool use is the use of two or more different kinds of tools of different functions on the same goal, traditionally referred to as a tool set.[1] Only two non-human species have been described to use tool sets in the wild beyond the anecdotal,[5] chimpanzees and, as we only very recently learned, Goffin's cockatoos.[1,6,7]

Chimpanzees stand out for their use of tools in terms of variety, diversity, and cognitive-cultural dependence on tool use.[8–10] They have demonstrated a great capacity to innovate solutions to physical problems through the use of tools, which differ between geographical regions, resulting in a remarkable cultural richness.[11]

In 1995, Suzuki et al. found that chimpanzees in the N'doki forest (northern Congo) used a set of tools to fish for termites[7]—a cultural innovation that facilitates access to the termite nest, subterranean or epigeal.[10,12] The tools used by these Congo chimpanzees have at least two complementary characteristics and functions: a perforating stick (short and rigid) used to pound a hole in the termite mound, and a fishing probe (long and flexible), to access the deeps of the mound and extract aggressive soldier termites.[12,13]

This finding sparked a decade-long debate on action planning abilities involved in chimpanzee termite fishing. Importantly, in 2004, Richard Byrne acknowledged that the N'doki chimpanzees may not identify the use of a tool set as a solution to a single problem but may instead perceive each tool as an independent solution to a different, unrelated problem (a termite mount being blocked; entering an open mount through slim channels).[14]

After years of research in the southern region of Noubalé-N-doki National Park (Goualougo Triangle), Crickette Sanz and David Morgan, together with Richard Byrne himself, rejected the previous argument after the former observed that the chimpanzees not only transported both tools at the same time but also did so in a flexible manner, according to present need[15]: chimpanzees carried only the fishing probe or both the fishing probe and the perforating tool depending on the conditions of the termite mounds, omitting redundant and unnecessary steps.[15]

Goffin's cockatoos are extremely opportunistic extractive foragers from a small archipelago in the Molucca region of Indonesia. Captive studies show that they are highly capable of innovating solutions to physical problems including tools[16–19] at the level of specialized tool users such as New Caledonian crows or the great apes, innovating complex associative tool use such as composite tools.[20] We recently also learned that they can manufacture and use a complex set of up to three different tools specifically crafted out of wood for three different functions (a sturdy tool for wedging, a slim tool for cutting, and a long, broad tool for spooning). The tools are flexibly used in sequence to access the seed content of a local fruit stone.[6]

Goffin's cockatoos, unlike other tool-using birds, are neither specialized on nor morphologically adapted to tool use.[21] Like in primates, their innovative capacity thus seems to largely depend on domain general cognition[16,20] and on knowledge actively acquired through exploration and playful object combinations.[22,23]

In the aforementioned tool set, Goffin's were holding the fruit stone (goal) in their claw while crafting and using each tool, and only a single tool could be held at a time.[6] This raises the historical doubts stated above regarding the planification of the use and categorization of both tools as a tool set: we do not know whether Goffin's have the capacity to identify a tool set or if they build and use specific tools for individually perceived substeps of the problem.

Inspired by the kinds of tool sets that Congo Basin chimpanzees use and transport for termite fishing, we designed a series of experiments to test the flexible use and transport of a tool set in Goffin's under controlled circumstances.

In the first experiment (fishing cashews), the cockatoos were exposed to a previously unknown tool set problem requiring the use of two different tools, one short and rigid (to tear open a membrane) and one long and flexible (to reach a reward behind that membrane—notably, it is too flexible to perforate the membrane directly; Figures 1A and 1D). Birds had to innovate and constantly master the use of the required tool set to proceed to further steps. We studied their learning progress in selecting the correct tool (the short one) for the first insertion, as well as their movements before inserting the tool for the first time.

In the second experiment, cockatoos faced two alternative apparatuses in a randomized sequence, one requiring the use of both tools (Figure 1A) and the other requiring only the use of the long, flexible probe (Figure 1B). Our goal was to test their flexibility in selecting the correct tool(s) from the tool set for each task.

The third and final experiment was similar to the second (either the two-tool or the single-tool apparatus presented in semi-randomized order), but reaching the box with the tools required additional movement. After two initial phases, one requiring climbing and the other requiring a horizontal flight, they faced a vertical flight phase to reach the box (Figure 2). The reason for the incremental effort increase from the walking (phase 1) to the horizontal and finally the vertical flight (phases 2 and 3)[24,25] was to be able to identify (to some extent) the minimal investment required for the birds to switch from transporting the tools individually to transporting two tools at the same time. We decided against counterbalancing the phases to avoid birds starting with the highest investment phase already having fallen into a habit of transporting both tools when later tested in the low investment phase.

We tested if birds would transport the tools as a set: therein, we were also interested in whether the probability of transporting both tools would increase relative to the presence of the box with a membrane. Transporting the tools individually when a tool set is needed (depending on the box type) requires a higher energy investment. The highest investment would be expected in the third phase (requiring a vertical flight).[24,25] Likewise, a wrong

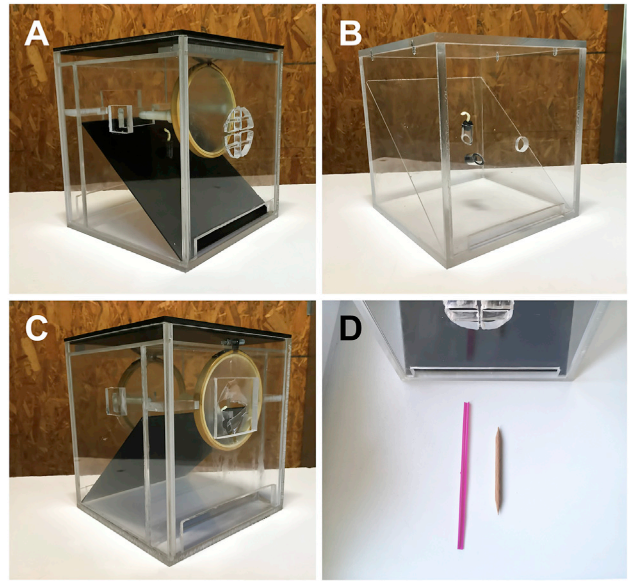

Figure 1. Boxes and tools
(A) Tool set box.
(B) Single-tool box.
(C) Backside of the tool set box with an embroidery ring (broken membrane) as it is displayed during the training phase.
(D) Long and flexible tool at the left; short and rigid tool with sharp ends at the right.
See also Figures S3 and S4 and Video S1.

decision is also costly when transporting both tools and only one is needed. Therefore, if their recognition of the problem includes the use of a tool set, we expect them to eventually transport both tools at the same time to the apparatus, and we expected them to transport the tools together more often when both tools are required to solve the task than when one tool is sufficient. Throughout this series of experiments, we revealed the ability of Goffin's to innovate the use of a tool set, as well as to use and transport it in a flexible way, thus suggesting the ability to categorize both tools as a tool set.

RESULTS

Experiment 1 (fishing cashews): Cockatoos can innovate the use of a tool set

Out of 10 cockatoos, 7 innovated the use of a tool set eventually and 6 of them reached the proposed criterion of 9 consecutive successful trials. There were 2 cockatoos, the adult male Figaro and the adult female Fini, that solved the task on their first trial with very short trial times (see below). There were 2 more cockatoos that were able to solve it in their second session and 2 more in their third. There was 1 cockatoo, the adult male Muki, that solved it later in the experiment but only on a single trial.

The individuals who solved the test showed notable differences in their ripping technique after the membrane had been punctured. Accessing the reward behind the membrane using a flexible tool requires some skill in tearing the membrane in a way that the nut can be reached in a straight line through the window. For most individuals, the tearing ultimately traced

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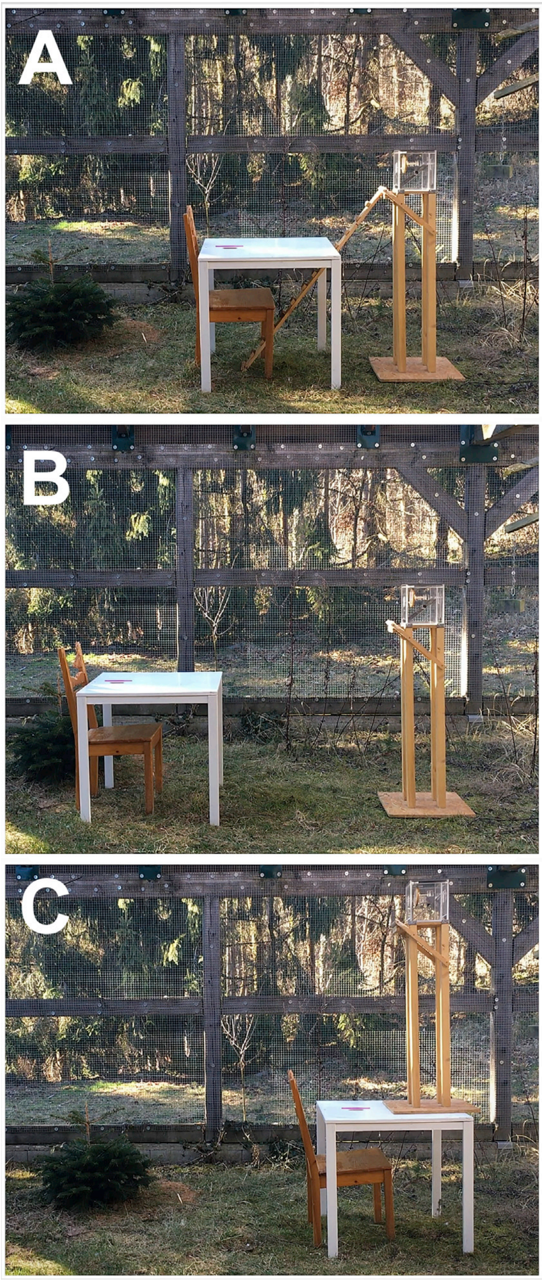

Figure 2. Platform and table setups during experiment 3
(A) Walking phase.
(B) Horizontal flight.
(C) Vertical flight.
See also Figure S4 and Videos S3 and S4.

horizontal or diagonal lines. Through these horizontal or diagonal holes, the second tool was introduced and, by means of a sweeping movement, the nut was hit.

Figaro and Fini stand out among the 6 solvers: both have repeatably demonstrated innovative competence in a tool-using task in previous studies.[16,19,20] Both solved this task on their first trial, reaching criterion (3 consecutive successful sessions) in the earliest possible time, and never failed to obtain the reward. On

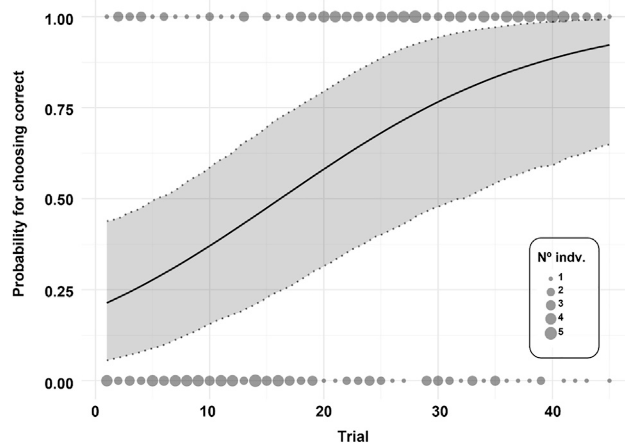

Figure 3. Probability to choose correctly over trials (experiment 1)
Solid line indicates the fitted model, and gray areas represent 95% confidence intervals derived by 1,000 bootstraps; circle sizes indicate the number of individuals choosing correctly/incorrectly for each trial.
See also Figure S2 and Video S1.

his first trial, Figaro needed only 31 s to explore the box, test both tools, and find the solution (Video S1). Fini needed 34 s.

After solving their first session, most birds did not fail a single trial again throughout the whole experiment (only one bird did, Dolittle).

Although with differences between individuals, all solvers started showing switching behaviors between the two tools, grabbing and releasing and alternating them multiple times before the first insertion.

When analyzing which variables (trial, switching, time until solving the task) were associated with the probability to choose the correct tool, we found an overall significant effect of the fixed effects predictors when testing the reduced model against the null model indicated (likelihood ratio test comparing full and null model: $\chi^2 = 9.617$, df = 4, p = 0.047). However, the two-interaction between the trial number and switching was not significant (Table S1). After removing this, we found that the time required to complete a trial was not associated with the probability of choosing the "correct" tool, but individuals tended to improve performance over trials (Figure 3), and the probability of choosing correctly increased if a switch of tools occurred before employing the tool on the task (Figure 4; Table 1).

We also analyzed what influenced switching behavior. The full-null model comparison revealed a significant influence of the test predictors ($\chi^2 = 6.781$, df = 2, p = 0.0336) and found that the time required to solve the task did not have an effect on switching events (GLMM: $\beta = -0.029$, SE = 0.243, $\chi^2 = 0.015$, p = 0.902); however, significantly more switches occurred in later trials (GLMM: $\beta = 0.943$, SE = 0.302, $\chi^2 = 5.862$, p = 0.0155; Figure S1; Table S2).

Experiment 2 (tool set flexibility): Cockatoos can flexibly use a tool set

Those 5 individuals who solved the first experiment, and were given the full 15 sessions, had the opportunity to participate in the second experiment (Dolittle had dropped out due to a lack of motivation).

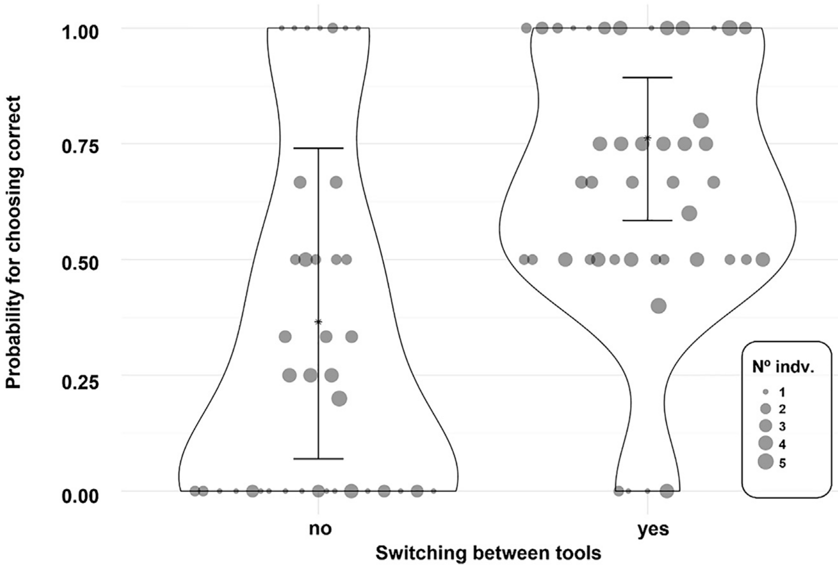

Figure 4. Influence of switching on the probability to choose correctly over all trials (experiment 1)

Violin plots indicate the distribution of data and the size of gray dots indicate the number of individuals switching; asterisks indicate fitted model means and error bars represent 95% CI based on 1,000 bootstraps.

See also Figures S1 and S2, Tables S2 and S3, and Video S2.

In this experiment in which the box requiring a tool set was semi-randomly alternated with a box requiring only the long tool (single-tool box), subjects performed 128 correct insertions of the first tool and 22 incorrect ones of which only 4 occurred with the single-tool box.

Overall, we found a significant effect of the test predictors on the probability of using the correct first tool (full-null model comparison: $\chi^2 = 16.477$, df = 8, p = 0.036). However, the three-way interaction between box type, switching, and trial number appeared non-significant (Table S3). After the removal of this and other non-significant interactions, we found clear significant effects of trial number and box type. We found a significant improvement in the probability of choosing the correct tool with increasing trial number (Figure S2; Table 2) and a difference between box types, with the probability of choosing the correct tool being higher when confronted with the single-tool box (Figure S3; Table 2). Neither time nor switching tools significantly affected the probability of choosing the correct tool.

Experiment 3 (tool set transport): Cockatoos can flexibly transport a tool set

In this last experiment, once again, the 5 individuals who completed the first experiment participated. There were 4 of them that eventually transported both tools together, and 3 of them did it recurrently (Figaro, Pipin, and Kiwi).

All three individuals transported both tools significantly above chance expectation when faced with the tool set box. By contrast, when faced with the single box, only Kiwi differed from chance expectation by transporting the single tool more often, whereas the other two individuals did not differ from chance level (Table 3).

During the first phase (climbing a ladder) of the experiment, all individuals started transporting the tools individually, with a single wing flap jumping from the table to the perch on the platform.

During this first phase of the experiment, one individual (Pipin, an adult male) began carrying both tools in both conditions. As other individuals would do in later phases, he inserted the short tool into the long one (halved straw), transporting them as a compound object (Figure S4; Video S3). Importantly, Pipin was missing some primary feathers and had to actively climb each step of the ladder. No other cockatoos transported both tools simultaneously during this phase.

Notably, during this and the subsequent phases, Pipin readjusted his tool choices several times before and during the climbing (Video S2).

During the second phase of the experiment, the cockatoos had to fly horizontally to reach the platform (Pipin still relied on the ladder—for him, the tools were placed farther apart to increase his energetic investment; see STAR Methods for details).

Pipin continued transporting the tool set, but now he always carried both tools in the tool set condition (5/5 times) and less often when the single-tool box was present (4/7).

Another individual started transporting both tools during this phase, Kiwi.

During the third and last phase of the experiment (vertical flight condition for 3 birds—even greater tool distance for Pipin; see STAR Methods for details) all 4 individuals transported both tools at once in flight eventually.

All of the flying cockatoos used various techniques to minimize effort, both on the way up and on the way down, which indicates that flying was costly.

Pipin continued to carry both tools every time he encountered the tool set box (22/22) and also transported both tools occasionally to the single box, but on half as many occasions (11/22). Kiwi, having transported for the first time in the last trial of the previous phase, from session five of this phase onward, transported both tools on all occasions when confronted with the tool set box (17/17) and only very rarely when confronted with the single-tool box (5/16). Figaro transported both tools together in session 8 (facing the tool set box), and from session 9, he transported whenever he encountered the tool set box (9/9 tool set transportation for session 10 onward but also in 7 out of 9 trials in the single-tool condition). Fini transported both tools together on only one occasion during the fourth session when she was facing the tool set box.

One bird (Zozo) never transported both tools together.

DISCUSSION

In our first and second experiments, we provide the first controlled evidence that the majority of Goffin's spontaneously innovated tool set use under controlled experimental conditions, without social facilitation, and learned to apply it flexibly according to need. Furthermore, our third experiment suggests that the

Table 1. Results of the fixed-effects part of the final reduced model on the probability to choose the correct tool

Term	Estimate	SE	Lower CI	Upper CI	χ^2	df	P	Min	Max
Intercept	−0.552	0.729	−2.6495	1.0755	–	–	[c]	−1.240	0.457
Trial[a]	1.072	0.334	0.4988	1.9864	5.164	1	0.023	0.817	1.394
Switch[b]	1.719	0.675	0.4049	3.791	5.077	1	0.024	1.103	2.209
Time[a]	−0.097	0.301	−0.8295	0.5101	0.111	1	0.738	−0.202	0.230

Estimates, together with standard errors, confidence intervals, test results, and minimum and maximum of model estimates obtained after dropping levels of random effects one at a time. See also Figure S1 and Table S1.

[a]Trial number and time were z-transformed to a mean of zero and a standard deviation of one; mean (SD) of trial number was 22.0 (12.5); mean (SD) of time was 100.2 (91.5)

[b]Switch (switching) was dummy coded with "no" being the reference category

[c]Not indicated because of having a very limited interpretation

tool set is more than just the use of tools in sequence (as historically suggested for chimpanzees before the flexibility of their tool set transport was observed; see introduction): four Goffins were observed to transport two tools simultaneously, and two Goffin's were able to not only transport their tool set together but even showed some flexibility depending on the task requirements. This suggests that, like in chimpanzees,[15] two tools may be categorized as a tool set.

In the first experiment, subjects innovated the puncturing and tearing of a membrane, a yet unreported mode of avian tool use.[1] There are no known cases of cutting tools in either wild primates or birds[1,26] beyond perhaps the second tool in the Goffin's original tool set study on Tanimbar.[6] However, in captivity, cases of cutting tool use have been documented in great apes[27,28] and in capuchin monkeys.[29] Sticks with puncturing function are indeed the first commonly used tool type in the Goualougo Triangle (Congo) to open epigeal or subterranean termite mounds before applying another tool within a tool set.[12]

The way certain subjects initially solved the task, dropping the short tool right after having used it to tear the membrane, is reminiscent of previous experimental results where cockatoos would drop a tool that was too short upon sight of the apparatus without using it and would manufacture a longer one.[30]

The way in which they solved these first trials does not yet require the categorization of both tools as a tool set. As Byrne suggested following observations of tool set use in chimpanzees, they could be using several tools with complementary functions in sequence in which the use of the second tool of a tool set could only be the result of the outcome of the use of the previous tool.[14] For example, during Figaro's first interaction with the box (Video S1), the use of the first tool is not immediately succeeded by the use of the second tool: it is only after walking around and exploring the box and after picking up and discarding the first tool again that the second tool is picked up and used.

The birds had to innovate the destruction of the membrane that required first a stout piercing push followed by a forceful wagging type of movement with the short stout tool. The destruction of the membrane would then allow for the full sight of the food reward and thereby possibly trigger the switch to the probing tool. Although they had a pre-experience session in which they learned that the membrane can be destroyed without the use of tools, it is reasonable that the tearing of the membrane was facilitated by the extensive experience in using sticks as tools of these subjects.

Figaro stood out: unlike the rest, he ripped through the membrane vertically, and throughout the experiment, he perfected his technique until he barely needed a mere closely centered pinhole. Through this small hole, he directed the longer tool with extreme precision toward the nut (Video S1). Figaro is the most experienced tool user in the sample,[16,17] using tools regularly outside of experiments as a means to explore and play (personal observation). His efficiency and effectiveness are probably the result of two non-exclusive factors, his particular technique for inserting the sticks[17,20] and a great deal of practice in different contexts.

Over the 15 sessions of experiment 1, the birds showed learning, gradually improving on the choice of the correct tool order to solve the tool set box (Figure 3). In the process, we observed a lot of switching behavior between the two tools (Figures 4 and S1). It is likely that picking the short tool initially required some level of impulse control as only the long tool had a direct reward association (Video S2).

Table 2. Results of the fixed-effects part of the final reduced model on the probability to flexibly choose the correct tool

Term	Estimate	SE	Lower CI	Upper CI	χ^2	df	p	Min	Max
Intercept	3.214	0.677	2.430	8.469			[c]	2.866	4.758
Trial number[a]	0.722	0.306	0.214	1.787	5.708	1	0.0168	0.540	1.287
Box[b]	−1.914	0.693	−6.154	−0.816	7.650	1	0.005	−3.415	−1.551
Switching[b]	0.202	0.545	−1.129	1.761	0.140	1	0.707	−0.027	0.577
Time[a]	−0.100	0.231	−0.638	0.592	0.185	1	0.667	−0.199	−0.038

Estimates, together with standard errors, confidence intervals, test results, and minimum and maximum of model estimates obtained after dropping levels of random effects one at a time. See also Figures S2 and S3.

[a]Trial number and time were z-transformed to a mean of zero and a standard deviation of one; mean (SD) of trial number was 15.5 (8.7); mean (SD) of time was 53.0 (73.9)

[b]Box and switching where dummy coded with "single" and "no" being the reference categories, respectively

[c]Not indicated because of having a very limited interpretation

Table 3. Results of the binomial tests for the 3 tool set transporters

	Box = d				Box = s			
	Transport correct tool				Transport correct tool			
Individual	No	Yes	p value[a]	Percentage "yes"	No	Yes	p value[a]	Percentage "no"
Kiwi	6	17	0.03469	0.739	17	5	0.0169	0.773
Pipin	0	22	0.00000048	1.000	12	11	1	0.522
Figaro	2	11	0.02246	0.846	3	7	0.3438	0.300

To evaluate if individuals transport the appropriate tools to the corresponding box, i.e., tool set to box "d" and single tool to box "s."
[a]p value of binomial test against p = 0.5

Switching behavior did not disappear throughout experiment 1 but increased. Interestingly, the probability of correctly choosing the tool was higher when the birds showed switching behavior prior to insertion (Figure 4). This may have several non-exclusive reasons, such as birds that use more haptic exploration being able to improve their performance. Additionally, a bird may impulsively pick up the food-associated tool (long tool) and drop it to pick up the short, stout tool upon seeing the intact membrane.

Switching behavior toward the correct option has been observed in previous experiments in which the Goffin's cockatoos had to choose between identical objects of different weights,[31] as well as when selecting among different tools to solve a problem.[20] Recently, movement during decision-making has been used to study metacognition through uncertainty and confidence in chimpanzees and capuchin monkeys, respectively.[32,33] Switching behavior in these birds could thus serve as a future means of studying their metacognition.

In the second experiment, cockatoos were confronted with both single-tool and tool set tool boxes in a semi-randomized fashion. This part of the study was designed to enable the animals to differentiate the operational properties of our two experimental apparatuses to thereby set a certain level of pre-experience for the tool transport phase.

The five individuals who proceeded into this experiment chose the correct tool above chance expectations from the start (Figure S2). Nevertheless, they still improved as the experiment progressed.

The aim of the third experimental design was to test whether Goffin's cockatoos would categorize both tools as a tool set[15] or whether the use of a second tool would only be the outcome of the use of the previous tool.[14]

Goualougo Triangle chimpanzees transport a single tool or a tool set (together) to catch termites in a somewhat flexible way depending on the circumstances.[15] As mentioned earlier, it has been argued that this cannot be explained by two isolated tool uses triggering one another.

Since our goal here was only to test for the Goffin's identification of a tool set, we left the box fully visible to the subjects. Nevertheless, derivations of the same setup may serve in future experiments to address other questions such as the mental imagery of future situations.

Three birds continuously transported both tools together in experiment 3 (Kiwi, Figaro, and Pipin). Interestingly, they always transported both tools together as a compound object. However, we must be cautious of how we interpret this action since the combination of the two objects was strongly facilitated by their shape. Future studies will allow us to explore their ability to transfer what has been learned to other object shapes and conditions.

Once they learned to transport both tools together (when they did it more than a single time), they transported every single time that they encountered the tool set box. Less frequently, they also transported both tools to the single box. There were individual differences in the decision to transport one versus two tools when faced with the single-tool box. Figaro transported both tools to the single-tool box nearly as often as he did to the tool set box. Pipin, on the other hand, transported the tool set twice as often when encountering the tool set box than when confronted with the single-tool box. Finally, Kiwi rarely made any errors. The unnecessary tool set transports of Figaro may be due to the consolidation of an inflexible strategy and/or due to a possible trade-off between attention and the likely low energetic cost of transporting both tools together. The two possibilities are not mutually exclusive since transport flexibility can be expected to be influenced by the cost of each wrong choice (and this is dependent on each individual). Unnecessary tool set transport may result from a trade-off between the physical effort invested in transporting an extra tool and the cognitive effort required in making an informed decision on the task at hand relative to the available tools. Moreover, it is noteworthy that an incorrect decision was more costly when a single tool was transported to a box with a membrane than when two tools were transported to a box with no membrane (in the first case, it requires going and coming back with a new tool, whereas in the second case, the extra cost is that of picking up and transporting two tools together).

Throughout the phases of the third experiment, effort may have played a role in the propensity to transport both tools. The early onset of transporting both tools together by Pipin, who was flightless, may be caused by different levels of effort. The effort required to actually climb the ladder (instead of hopping over the ladder from the table to the perch with a single wing flap as other birds did) led him to a more slow-paced approach, also allowing him to make mid-way adjustments of his selected tools to transport (Video S2).

The presumably higher energy cost of vertical flight may have had an effect on the first tool set transport of Figaro and Fini (Video S3), as in the consolidation of Kiwi's transport at that phase. Fini, the only individual that did not continue transporting both tools after having done it once, was also the only female left in the experiment and is considerably weaker and smaller than Figaro and Kiwi.

Notably, experiment 3 may have had a particularly challenging spatial layout. The cockatoos needed to adapt their behavior to the narrow space between the perch and the box on top of the platform (Video S4). This space was an important conditioning factor for two technical aspects: the insertion of the tools (especially the long one) and placing the long tool on the platform for later use.

Individuals who transported both tools were obliged to temporarily lay aside one of the tools to be able to use the other; letting the second tool stay on the platform was a challenge in such a limited space, and some mastered it sooner than others. Although the most common strategy here was the release of the long tool very close to the box wall, Figaro developed one in which he held on to the second tool by keeping it elevated with one foot while inserting the first with the beak (Video S4). The development of different techniques supports the innovative nature of this tool-saving behavior.[34]

As documented in previous experiments,[17,20] the technique used for tool insertion was different among the Goffin's, and this affected the way both tools were used in the confined space of the platform. For example, when Fini grasped the long tool, she adjusted it before flying so that the long end was facing her left cheek. In this way, when she reached the top of the platform, she was not hindered by the confined space to rotate the tool to her preferred position (Video S2). We hope that future experiments will allow us to investigate whether the gripping behavior of tools by cockatoos includes seeking an end-state comfort effect.[35,36]

Based on the results presented here, we suggest that tool set use by Goffin's cockatoos results from individual innovation but seems to be within the capacity of the species (notably, in a more limited capacity, also in wild settings).[6] The identification of a tool set in anticipation of future need additionally requires the cognitive capacity to make task-dependent decisions about when to transport more than one tool. This ability seems to be constrained by general cognitive flexibility and a possible trade-off between attention and task effort. It thus remains limited to certain individuals. Our results also open the door to future studies in which we will explore their ability to plan actions over a longer period of time but investigate possible anticipation through end-state comfort effect and explore switching behavior as a possible tool to study metacognition.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2023.01.023.

A video abstract is available at https://doi.org/10.1016/j.cub.2023.01.023#mmc7.

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AUTHOR CONTRIBUTIONS

Conceptualization, A.J.O.-M. and A.M.I.A.; funding acquisition, A.M.I.A., S.T., and S.R.B.; conducted experiments, A.J.O.-M.; data analysis and visualization, A.J.O.-M., M.O'H., and R.F.; writing – original draft, A.J.O.-M.; writing – review & editing, A.J.O.-M., M.O'H., R.F., S.T., S.R.B., and A.M.I.A.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Experimental models: Organisms/strains		
Goffin's cockatoo (*Cacatua goffiniana*)	Goffin Lab (Vienna)	N/A
Software and algorithms		
BORIS v.7.4.3	Friard and Gamba[37]	https://www.boris.unito.it/
R v.4.0.2	R Development Core Team[38]	https://www.r-project.org
Other		
JVC GZ-HM30	JVC	https://de.jvc.com/microsite/de/hdeverio/lineup/hd_memory.html
NEX-5	Sony	https://www.sony.com/electronics/support/e-mount-body-nex-5-series/nex-5

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Antonio J. Osuna-Mascaró (Antonio.OsunaMascaro@vetmeduni.ac.at)

Materials availability

This study did not generate new unique reagents.

Data and code availability

- All datasets used for analysis in this study have been deposited at Science Data Bank (file: Flexible_tool_set_transport.RData) and are publicly available as of the date of publication (ScienceDB: https://doi.org/10.57760/sciencedb.06613).
- All code generated during this study has been deposited at Science Data Bank (files: Flexible_tool_set_transport.R, and Flexible_tool_set_transport_functions.R) and is publicly available as of the date of publication (ScienceDB: https://doi.org/10.57760/sciencedb.06613).
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Subjects and housing

10 adult cockatoos (7 males, 3 females) were selected for the experiment. Two additional females were initially intended to partake in the experiment, but were removed from the experiment before habituation was completed. The birds are housed throughout the year in an environmentally and socially enriched habitat in the Goffin Lab. The laboratory facilities comprise an indoor climate-controlled area (45 m2; 3 to 6 m high) as well as an outdoor aviary (ca. 200 m2; 3 to 4.5 m high). Climate control ensures a minimum temperature of 17°C during the winter, with light and dark cycles of 12 hours each.

The 10 birds selected for this study had tooling experience from previous experiments, including several experiments with sticks (e.g., Auersperg et al.[16,17,30] and Laumer et al.[19]), and associative use of tools (stick and ball combined),[20] and safekeeping of sticks.[34] None of them had experience in using sharp tools for poking and tearing surfaces, nor in carrying more than one tool at the same time.

Ethics statement

As our experiments were purely appetitive and strictly non-invasive, they were classified as non-animal experiments in accordance with the Austrian Animal Experiments Act (TVG 2012). Nevertheless, these experiments were also approved by the Ethics and Animal Welfare Committee of the University of Veterinary Medicine Vienna in accordance with good scientific practice guidelines and national legislation.

METHOD DETAILS

Apparatuses

Three experiments were carried out; in experiment 1 "fishing cashews" the tool set box was used (Figure 1A), in experiment 2 "tool set flexibility" the tool set and single tool box were used (Figures 1A and 1B), and in experiment 3 "tool set transport" both boxes were used, as well as an elevated platform (with or without ladder) and a table (Figure 2). A chair was used as a starting position for all experiments.

The tool set box is made almost entirely of Plexiglas (height 22.5cm, width 20cm, depth 20cm), with a slide and a lid tinted in black, the rest being completely transparent (Figure 1A). On the ramp there is a small vertical stand, where a piece of cashew nut is placed to be knocked down. The front wall (which can be removed, to replace the reward) has a lower opening, to collect the nut, and another central one, as a window, divided into 8 spaces (diameter 5.2cm). The lid can be removed and a wooden embroidery ring (diameter 11cm; staying 5cm away from the window) can be placed inside (between the window and the nut holder). A paper membrane of only $14g/m^2$, slightly impregnated with rapeseed oil to make it more transparent, is placed on the embroidery ring.

The posterior side of the box has a double wall, leaving a gap of 3.2cm deep between them. The outermost wall also has a lower opening and a window (in this case square; 3.2cm in height, 16.5cm in width). An embroidery ring with membrane can be positioned in the resulting space between the two walls, leaving behind a small nut shelf on the inner wall. When a membrane is placed, it is 2cm away from the window, so that it is accessible without the use of any tools.

The single tool box is also made of Plexiglas, and has the same general dimensions as the tool set box (height 22.5cm, width 20cm, depth 20cm; Figure 1B). It is completely transparent, and also has a slide with a stand for rewards. The front wall also has two openings, a lower one, to collect the knocked-down nut, and a window (in this case much smaller than that of the tool set box, only 2cm in diameter). In the single tool box only one tool is needed to obtain the prize (the long flexible tool).

The elevated platform is constructed of wood, and has a space designed for the placement of either one of the two boxes, tool set or single tool (Figure 2). The height of the platform is 104cm, and it has a supplement that can be attached as a ladder/ramp, also made of wood (127cm total length; 42cm of travel from the table, with 55° of inclination).

General procedure

Three consecutive experiments were carried out with a single, initial, successful pre-experience session common to all of them.

Pre-experience

As previously mentioned, the subjects selected for the experiment were already experienced in the use of sticks as a tool, both rigid and flexible. No previous experiment had required tearing a membrane, or breaking a structure using tools, which is why the cockatoos were given information that the paper membrane can be destroyed. To avoid shaping,[39] the pre-experience box was designed so that the membrane on the back side is accessible to the beak and can be ripped to retrieve a nut without the use of any tool (Figure 1C).

Once habituated, they received a single session of 3 trials of 5 min maximum with a nut fragment and a new membrane for each trial.

Testing

For all experiments the basic procedure was very similar. Sessions of three trials, with a maximum of 10 minutes each (the number of sessions is variable between experiments). If an individual reaches the time limit, and has not gained access to the nut, the trial is considered failed and the session is terminated. That individual must resume the experiment on the next day, and in the next session. Both tools were placed parallel to each other and perpendicular to the front window of the box. The position of the tools (left or right) was fully randomized throughout the experiments (we used random.org for all randomizations). The order of the boxes (single tool or tool set box) was also semi-randomized (both boxes appearing the same number of times but in random order) in the experiments where this was relevant (experiments 2 "tool set flexibility" and 3 "tool set transport"). If a tool falls into the box and remains in an unrecoverable position, as well as if it falls to the floor, a new similar tool is added to the initial position on the table.

First experiment, fishing cashews

In the first experiment, 11 individuals faced the tool set box (Figure 1A) for a minimum of 10 sessions and a maximum of 15. As in all experiments, they found both tools in front of the box, and separated from each other by about 3 cm. Similarly, if a trial was considered failed, the session was terminated and the same individual had to continue in the next session. To consider an individual as a consistent solver, a criterion of 3 consecutive solved sessions was used. Each subject had a minimum of 10 sessions to reach the established criterion, and those who reached it would receive 5 more sessions, up to a maximum total of 15 sessions.

Second experiment, tool set flexibility

Those individuals who mastered the use of the tool set faced a test where, over 4 sessions, they would semi-randomly find either the tool set or the single tool box in each trial. Both tools were always available.

Third experiment, tool set transport

The third experiment consisted of 3 different and consecutive phases, in which one box or the other was presented on an elevated platform under different conditions Throughout the third experiment, as in the previous experiment, the tool set and single tool boxes were semi-randomly alternated for each trial (although being random, we kept the total number of encounters with each box balanced). Before each trial, the subject was briefly lifted towards the box on top of the platform to give it an opportunity to identify it, and then placed on the top of the back of a chair that served as the starting position. For one individual (Pipin), who was unable to fly during the months of the experiment, phases 2 and 3 were adapted to also increase the effort at least to some extent.

Phase 1. During the first phase an elevated platform with a ladder attached was used, in a way that from the table it was possible to climb up to the box placed on top of the structure. It consisted of 10 sessions of 3 trials each. After all transporting birds except for the flight impaired Pipin simply solved the ladder by hopping onto the perch with a single wing flap instead of climbing it, two phases were added (horizontal and vertical flight) that required actual flight in order to increase the energy loss involved in transporting each tool individually:

Phase 2. The setup for this trial required brief short horizontal flight. The elevated platform was placed 85cm from the table (maintaining the same height of 30cm from the previous phase). For Pipin, the configuration of Phase 1 was maintained (with the platform close to the table, and the ladder attached), but the distance between both tools was increased from 3cm to 38cm. Four sessions were used in this phase.

Phase 3. The last phase of the experiment involved steep vertical flight and some landing skill. For this, the elevated platform was placed on the table, requiring a vertical displacement of 104cm. Each individual was allowed to observe the box from an elevated position, then they were placed in their starting position, and the trial began.

For Pipin, once again, the tools were moved to the furthest distance, reaching 73cm (the table is 75cm wide; Video S4). Fifteen sessions were used in this last phase of the experiment.

In this final phase, the conditions were also adapted to Fini, a height of 75.5cm was used for the platform.

Data collection

The experiment was recorded and analyzed in situ, as well as through the recordings, using coding software (BORIS 7.4.3).[37] The test trials were recorded with two cameras (JVC GZ-HM30 and Sony NEX-5). One camera recorded a general overview, and the other a more detailed view of the action close to the box. The positions of both cameras were slightly modified throughout the 3 experiments and phases to always achieve a good perspective independent of the cockatoo's position or movement.

We recorded the time taken per trial, the tool switching behavior (consecutive grabbing and releasing of one tool and another before the first insertion), the tool used for the first insertion, and the success or not getting the reward.

To determine which tool was used first we analyzed only the insertion through the window, regardless of whether the tool touched the membrane.

We considered as a tool switching behavior all sequences involving 3 consecutive grasps and 2 consecutive throws between different tools and no contact with the box in between; this involves, at a minimum, grasping and releasing one tool, to grasp and release another tool, and to grasp the initial tool again.

QUANTIFICATION AND STATISTICAL ANALYSIS

Statistical analysis

We performed a series of logistic Generalized Linear Mixed Models[40] to analyze:

The role of experience (experiment 1)

To test if the probability to solve the task depends on experience, we ran a first model using correct choice of first tool (short tool, no/yes) as a response variable. Within this model, we included trial number (continuous), switching (no or yes), time needed to solve the task (continuous), as well as the interaction between trial number and switching.

The progression of switching between tools (experiment 1)

Similarly, to investigate if the probability of switching depends on experience with the task, we ran a second model with switching as response variable. As fixed effect predictors, we included trial number and time needed to solve the task.

The flexibility in responding (experiment 2)

To test whether individuals are able to flexibly select the correct tool(s) when faced with a box requiring two tools (tool set box) as compared a box requiring only a single tool (single tool box), we ran a model with correct choice (using the short tool when facing the tool set box, and the long one for the single tool box) as response variable. Within this model we included box-type (tool set box or single box), trial number, switching and their interaction up to the third order plus time to solve the task as fixed effect predictors. Transportation of tools when necessary (experiment 3)

To analyze whether tool transport was more likely to be performed when necessary, we could only include those individuals who had transported the tool set recurrently. We conducted binomial tests for the 3 tool set transporters to evaluate if individuals transport the appropriate tools to the corresponding box (two tools to the tool set box and only the long tool to the single toolbox).

In all of the above models (experiments 1 and 2) we included individual as a random intercept effect to model variation among individuals as well as to avoid pseudo-replication. We included all possible identifiable random slopes to keep type I error rate at the nominal level of 0.05.[41,42] We removed correlations between random slopes and intercepts from the model when they were in part unidentifiable (with absolute correlation parameters estimated as 1).[43] The covariates trial number and time were z-transformed before including them into the model to ease model interpretation and model convergence.[44]

After fitting the full models, we confirmed that the none of the model assumptions were violated and assessed model stability. We verified absence of collinearity by calculating the Variance Inflation Factor (VIF) using the R package "car" version 3.0-12.[45] None of factors within the models exhibited signs of collinearity (max VIF: 1.19). Second, we visually inspected whether the best linear unbiased predictors (BLUPs) per level of the random effects were approximately normally distributed.[46] We assessed model stability with regard to the model estimates, by comparing the estimates from the model including all data with estimates obtained from models in which the levels of random effects were excluded one at a time.[47] This revealed the models to be of moderate to good stability with respect to both fixed and random effects.

To avoid 'cryptic multiple testing',[48] we compared each full model to its respective null model lacking fixed effects predictors but otherwise being identical in the random effects part. If this comparison was significant, we continued with testing the individual fixed effects. We did so by reducing model complexity and dropping non-significant interactions, from higher order to lower order terms, from the model one at a time and compare the simpler with the more complex model utilizing likelihood ratio tests.[41]

We fitted the models in R (version 4.2.0)[38] using the 'glmer' function of the 'lme4' package (version 1.1-27.1)[49] with the optimizer "bobyqa" with 100.000 iterations. We calculated confidence intervals for the model estimates by applying the function 'bootMer' of the package 'lme4', using 1,000 parametric bootstraps.

See supplemental information for further information on model details, output and model diagnostics.