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Report

Rooks Use Stones to Raise the Water Level to Reach a Floating Worm

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Summary

In Aesop's fable "The Crow and the Pitcher," a thirsty crow uses stones to raise the level of water in a pitcher and quench its thirst. A number of corvids have been found to use tools in the wild [1–4], and New Caledonian crows appear to understand the functional properties of tools and solve complex physical problems via causal and analogical reasoning [5–11]. The rook, another member of the corvid family that does not appear to use tools in the wild, also appears able to solve non-tool-related problems via similar reasoning [12]. Here, we present evidence that captive rooks are also able to solve a complex problem by using tools. We presented four captive rooks with a problem analogous to Aesop's fable: raising the level of water so that a floating worm moved into reach. All four subjects solved the problem with an appreciation of precisely how many stones were needed. Three subjects also rapidly learned to use large stones over small ones, and that sawdust cannot be manipulated in the same manner as water. This behavior demonstrates a flexible ability to use tools, a finding with implications for the evolution of tool use and cognition in animals.

Results

All four subjects (Cook, Fry, Connelly, and Monroe) solved the task (Figure 1), using stones to raise the water level to a height at which the worm could be reached (see Movie S1 available online). Cook and Fry were successful on their first trial, whereas Connelly and Monroe were successful from trial 2. However, only Connelly, Cook, and Monroe completed the experiments—Fry stopped approaching the apparatus after five trials, having had an adverse reaction to one of the worms—and hence only the results of these three subjects are reported here. We carried out three experiments. In experiment 1 we varied the starting height of the water, in experiment 2 we gave the subjects the choice of using large or small stones, and in experiment 3 we presented a control tube containing sawdust alongside the tube of water.

Experiment 1

Subjects were highly successful regardless of the starting level of the water and the number of stones needed (98.4% ± 1.6% of trials). They were also highly accurate, putting in only the exact number of stones needed to raise the water level to a reachable height (Figure 2A). They did not continue putting stones into the tube once this had been achieved and did not add any more stones once they had taken the worm. This suggests that the behavior was goal directed.

Subjects appeared to assess the starting water level before each trial, observing the tube from both the top and the side (Movie S1). They did not try to reach the worm after dropping each stone but rather dropped a number of stones in before first attempting to reach for the worm. This number was strongly correlated to the number of stones needed to raise the water level to the correct height, suggesting that, having assessed the starting level of the water, rooks translated this into an estimate of the number of stones needed. This estimate was fairly conservative: subjects tended to place one or two fewer stones into the tube than were actually needed before trying to reach the worm (Figure 2B). They then added extra stones as needed to top the level up to the reachable height.

Subjects were more accurate in their estimation when fewer stones were needed (Movie S2). The greater the number of stones needed, for example six or seven, the larger the error in their initial estimation. This is consistent with the suggestion that rooks assessed the level of the water and translated this into the number of stones needed at the start of the trial. However, we cannot rule out the possibility that rooks used the rising water level as continuous feedback after dropping in each stone. Further investigation will be required to investigate this effect, perhaps by covering the tube in an opaque film after showing the subject the starting water level.

Experiment 2

Overall, subjects used more large stones than small stones to solve the task (mean ± standard error of the mean [SEM]: large 3.08 ± 0.22, small 0.93 ± 0.09; Movie S3). There was no effect of trial on the number of large stones used (repeated-measures analysis of variance [ANOVA], $F_{19,38} = 1.35$, $p = 0.210$), but there was a significant effect of trial on the number of small stones used ($F_{19,38} = 4.56$, $p < 0.001$) and on the proportion of large to small stones used ($F_{19,38} = 4.15$, $p < 0.001$). All subjects initially chose a small stone on the first trial (Figure 3). When separating the trials into four blocks of five and looking at the first three stones used in each trial (a minimum of three stones were needed for success), we found a rapid improvement in the percentage of large stones chosen across blocks (means of 42%, 76%, 93%, and 100%). This result suggests that subjects did not possess an understanding of the relationship between the size of the stone and the volume of water the stone could displace and did not automatically choose the large stones following their use in the previous experiment (although this may have still influenced their speed of learning). Rather, they learned rapidly to use the large stones. One explanation is that they learned the usefulness of the large stones in displacing more water; however, we believe it more likely that the subjects received feedback in observing a larger rise in water level when depositing the large stones and obtained the reward more quickly when using the large stones. Regardless, subjects rapidly showed the ability to select and utilize this functional property of the stones in order to solve the task in the most efficient way.

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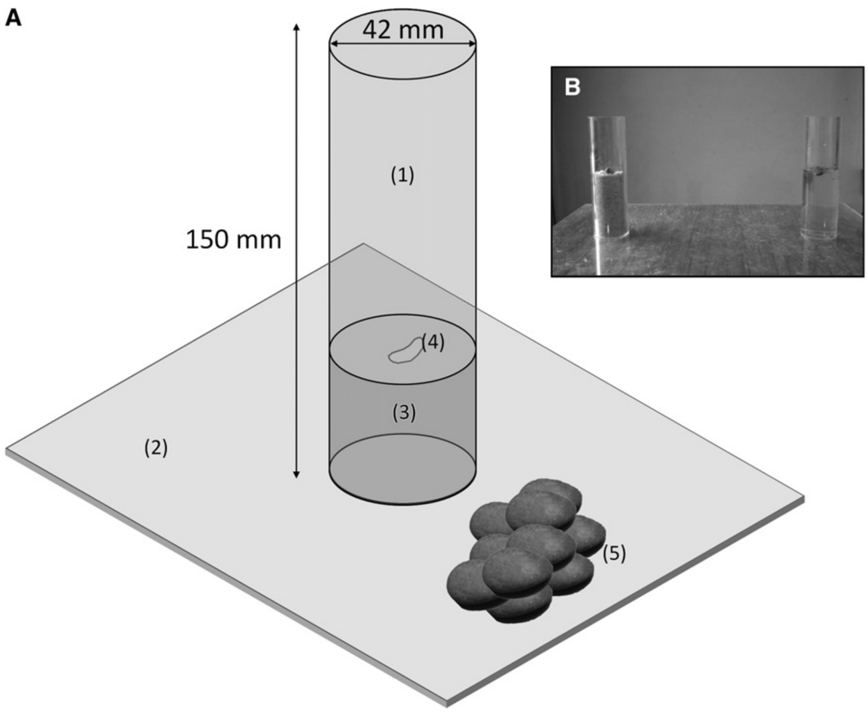

Figure 1. Diagram of Apparatus

(A) Setup used in experiment 1 and experiment 2. Sections (1) and (2) are clear Perspex; (3) water; (4) waxworm; (5) pile of stones. Ten large stones were used for experiment 1; five large stones and five small stones were used for experiment 2. (B) Photograph of experiment 3 setup. The tube at left contains sawdust; the tube at right contains water. (The position of tubes was pseudorandomized during the experiment.)

Experiment 3

Overall, subjects dropped more stones into the tube containing water than the tube containing sawdust (mean ± SEM: water 3.0 ± 0.14, sawdust 0.95 ± 0.22). However there was an effect of trial on the number of stones dropped into the water (repeated-measures ANOVA, $F_{19,38} = 1.87$, $p = 0.049$) and into the sawdust ($F_{19,38} = 2.12$, $p = 0.024$) and on the ratio of stones dropped into water compared to sawdust ($F_{19,38} = 2.42$, $p = 0.010$). There was also a difference in the initial performance of the subjects (Figure 4). Connelly and Monroe, who performed this experiment first and thus were naive to the use of stones in water, had an initial preference for the sawdust on trial 1; however, this was reversed by trial 2. Cook had a preference for the water on the first two trials (Movie S4), but he had been rewarded for dropping stones into the water tube in the two previous experiments. Again, when separating the trials into four blocks of five and looking at the first three stones used in each trial, all subjects showed an increase in the proportion of stones dropped in the water across blocks (means of 56%, 84%, 82%, and 87%). Because sawdust was a novel medium to the birds, it is not surprising that this property had to be learned. Cook never dropped a stone into the sawdust after trial 8, suggesting that his previous experience may have facilitated the speed of learning. Although the performance of the birds indicates that they did not immediately understand that the level of sawdust cannot be raised in the same manner as water, they rapidly learned to attend to and discriminate between the contents of the tubes.

Discussion

The results of these experiments provide the first empirical evidence that a species of corvid is capable of the remarkable problem-solving ability described more than two thousand years ago by Aesop. What was once thought to be a fictional account of the solution by a bird appears to have been based on a cognitive reality. Our evidence suggests that rooks not only are capable of solving such a demanding task but also appreciate the task affordances such as the rise in water level needed and the number of stones required to achieve this rise.

The initial solution to the task may have been derived from the birds' prior experience (see Experimental Procedures). Seemingly insightful behaviors (see [13] for a definition) may be achieved by "chaining" previously rewarded behaviors [14] or by generalizing from one task to another. Although the subjects' behavior can be explained in these ways, there is some reason to suggest that the behavior was not solely a conditioned action: multiple acts of stone dropping were necessary for success (in previous experiments, one stone had been necessary for success), and subjects did not try to reach for the reward after dropping each stone. In addition, they reached for the worm from the top of the tube (see Movie S1) rather than checking at the base (in previous experiments, the worm was accessible below the tube).

It is possible that the initial stone-dropping behavior was elicited by subjects' previous experience and that the increased proximity of the worm reinforced the initial stone drop, leading to a cycle of stone dropping until the worm could be reached. However, it is not clear that the worm getting closer would seem rewarding to the subject. Rather, the worm getting closer but still not being within reach might equally have been unrewarding or frustrating; hence, the behavior would be repeated only if it were goal directed. Furthermore, the subjects' persistence is suggestive of delayed gratification: continuing a behavior for a delayed reward while paying an opportunity cost for waiting because they cannot concurrently engage in other activities [15]. Alternatively, the reward may be seen as being on a ratio schedule; however, animals usually have to learn the schedule of reinforcement, and in the variable height test, the ratio was not fixed. Subjects repeated the stone-dropping behavior from the first trial without learning that multiple stone additions would lead to the reward, again suggesting that the behavior was goal directed.

The stone-dropping behavior might also be argued to be rewarding in itself (i.e., play behavior). Although we did not provide an independent control condition in which subjects were presented with a tube containing water but no worm, we found that subjects stopped adding stones once the worm had been reached and removed from the tube, providing evidence against this argument.

This study demonstrates the flexible nature of tool use in rooks; similar abilities have been demonstrated in great apes and proposed as candidates for insight [16, 17]. Orangutans

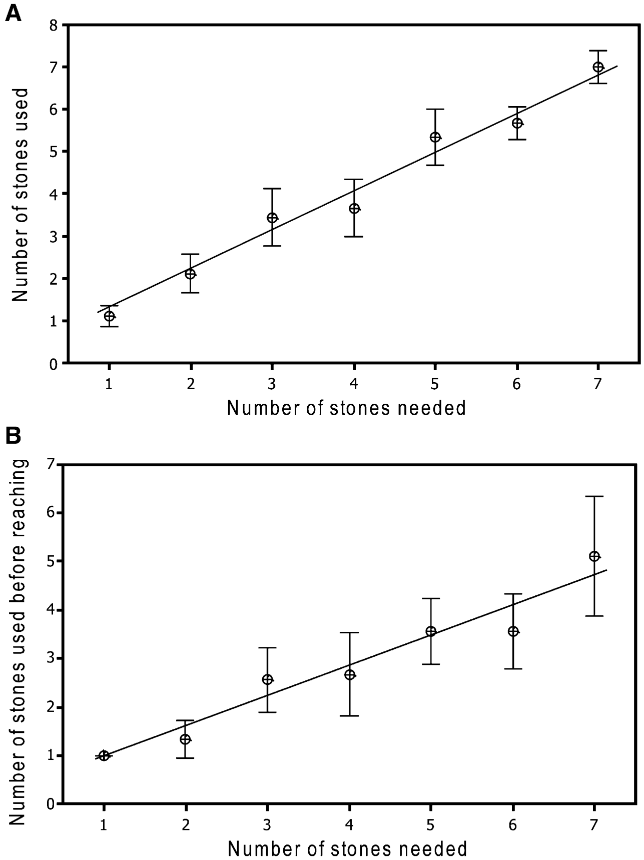

Figure 2. Experiment 1 Results

Graphs showing significant correlation between the number of stones required for success and the total number of stones used per trial (A) ($r^2 = 0.88$, $F_{1,61} = 460.38$, $p = 0.000$) or the number of stones used before first attempting to reach the worm (B) ($r^2 = 0.63$, $F_{1,61} = 104.16$, $p = 0.000$). Data points show mean; error bars show standard error of the mean. Line indicates linear regression.

have been shown to be capable of using water as a tool, transporting it in their mouths and spitting it into a tube to raise the level of a floating peanut that was otherwise out of reach [17]. However, that task was not directly analogous to Aesop's fable—in Aesop's fable, the water was not transported to the pitcher but was already present. Thus, the water in Aesop's context does not fit the standard definitions of a tool [1, 18]; rather, the stones are used as tools acting as displacing agents on a medium that can be manipulated by these agents.

Our results also showed that rooks learned to use large stones rather than smaller ones and that sawdust cannot be manipulated in the same manner as water. This suggests that although the subjects did not appear to "understand" the usefulness of the materials at first, they rapidly learned which stone size produced the reward soonest and also learned to discriminate between the two substrates. Some of the subjects' previous experience involved attending to the properties of stones and choosing between two tubes with different contents, and this may have facilitated rapid learning; however, an appreciation of task affordances, as suggested by the results of experiment 1, might work in tandem with rapid learning to produce sophisticated behavioral solutions to complex problems.

It is even more remarkable that this evidence comes from a species that does not appear to use tools in the wild. Solving the task constitutes a clear example of tool use. Hence, the evidence suggests that rooks rival animals that habitually use tools in the wild in their cognitive understanding of tool-related problems. This suggests that the cognitive solutions to physical tasks in this species stem from a general understanding of physical rules rather than a specialized adaptation to use tools [19]. We therefore have provided a direct response to the challenge posed by some primatologists who have claimed that great apes have a generalized cognition whereas corvid intelligence is based on a series of adaptive specializations [17]. Our data also provide further evidence for the idea of convergent cognitive evolution in these two distantly related groups. This is particularly interesting because the brains of birds and mammals are structurally very different [20].

Given our claim that rooks have a generalized cognitive ability that has not resulted from specialized behaviors, we may predict that other members of the corvid family might also share this general cognitive trait and hence would also be capable of solving the problem faced by Aesop's thirsty crow. Types of tool use reportedly practiced by members of the corvid family include the use of leaves, sticks, and twigs as probes; the shaping of hooks and their use to extract grubs from holes; the use of shells and rocks as hammers to open food items; the dropping of stones to displace intruders or prey; the use of paper as a rake and sponge; the use of a cup to carry water to dry food; and the use of a plug to form a pool of water [1–4]. The last two observations [1, 21] support the suggestion that corvids may appreciate the useful properties of water.

Given that some of the more distantly related members of the corvid family have been reported to use tools [22], we might speculate that the capacity is shared by all of the Corvidae. It is also interesting to note that, historically, the name "crow" was ascribed to almost all corvids. In folklore, it is rarely possible to know with certainty which corvid is being referred to [23]. Hence, Aesop's crow might have easily been Aesop's rook or Aesop's raven. In fact, a similar story was told by the first-century encyclopedist Pliny the Elder, who reported that a raven had been seen piling up stones in a memorial urn containing water during a time of drought.

We might ask: If all corvids possess the cognitive ability to use tools, why do some species such as rooks not use tools in the wild? Rooks exploit a number of different, readily available food sources, such as seeds, insects, carrion, and refuse, and as such may lack the motivation to use tools in the wild. Parallels can be drawn with capuchin monkeys, which have been known for many years to use tools in the laboratory but use them scarcely at all in the field [24], and only in certain ecological conditions such as when food is scarce [25].

Aesop used his fable to ascribe the moral that "necessity is the mother of invention." Our evidence suggests that in this case, it is cognitive generalization that may provide the toolbox from which the solution could be drawn.

Experimental Procedures

Subjects

Our experiments were conducted with four adult rooks, *Corvus frugilegus* (two males, Cook and Connelly, and two females, Fry and Monroe). These birds were part of a group of twelve hand-raised rooks housed in an outdoor aviary at the University of Cambridge Department of Zoology, Sub-Department of Animal Behaviour. All subjects were five years old at the time of testing. The four birds were in mated pairs (Connelly/Monroe, Cook/Fry). Outside of testing, the birds had ad libitum access to food and water.

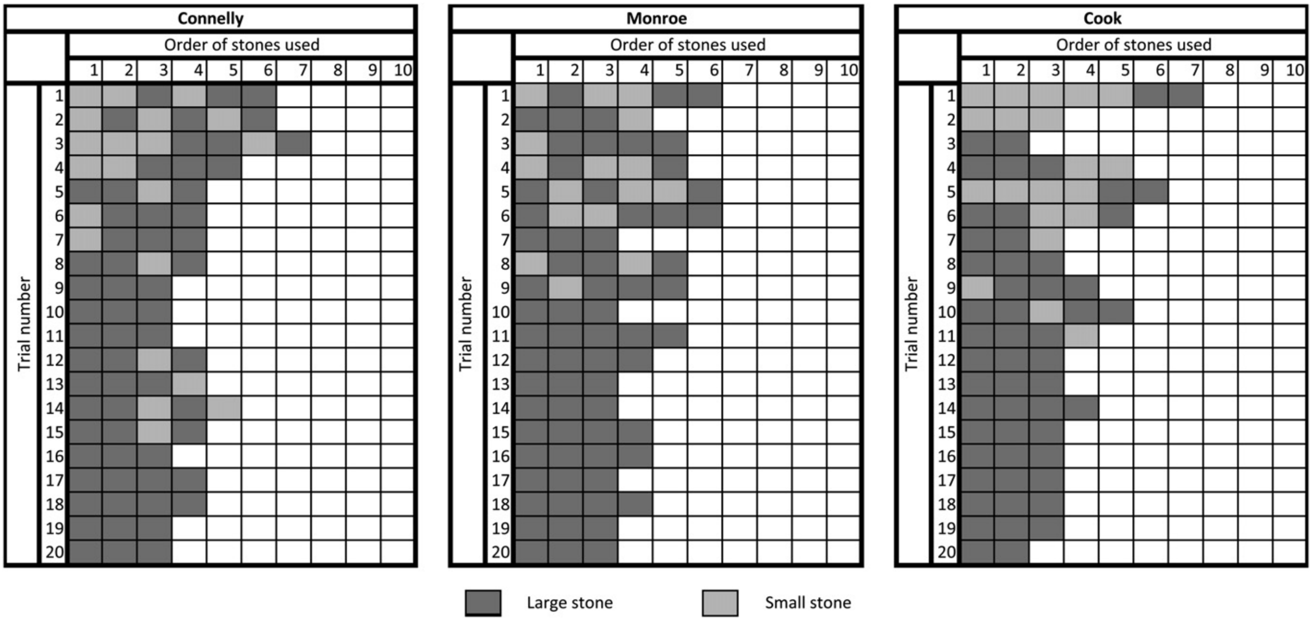

Figure 3. Experiment 2 Trial-by-Trial Description of Behavior

Subjects were successful if they used at least three large stones or a combination of two large stones and at least four small stones. (Note that Monroe was successful on trial 4 despite using one fewer small stone than needed and that Cook was successful on trial 7 despite using one fewer large stone than needed. This may be a result of experimental error, although it is also possible that the birds managed to stretch further into the tube than usual on these trials.)

Apparatus

We presented subjects with a vertical clear plastic tube containing a waxworm (wax moth larvae, *Achroia grisella*) floating on water at a level too low to be directly reached with the beak. Subjects were also provided with stones that could be used to raise the level of the water in order to float the worm to a height that could be reached (Figure 1).

Prior Experience

Subjects had encountered a similar apparatus before (a vertical Perspex tube), but not one containing water. When they had encountered the apparatus before, they had been required to remove a small cardboard bucket from the tube by using a stick and wire hook tool [26]. All subjects also had previous experience of using stones as tools, but they had never used stones in the way required in these experiments. Subjects had previously dropped stones onto a platform in order to collapse the platform [26]. They may also have previously seen stones in water (their aviary was lined with stony gravel and was provisioned with water trays for bathing and drinking), but they had never been required to raise the level of water by using stones.

Pretesting

For each subject, we adjusted the level of the water until they could just reach the worm without using any stones (the "reachable height"). Subjects differed

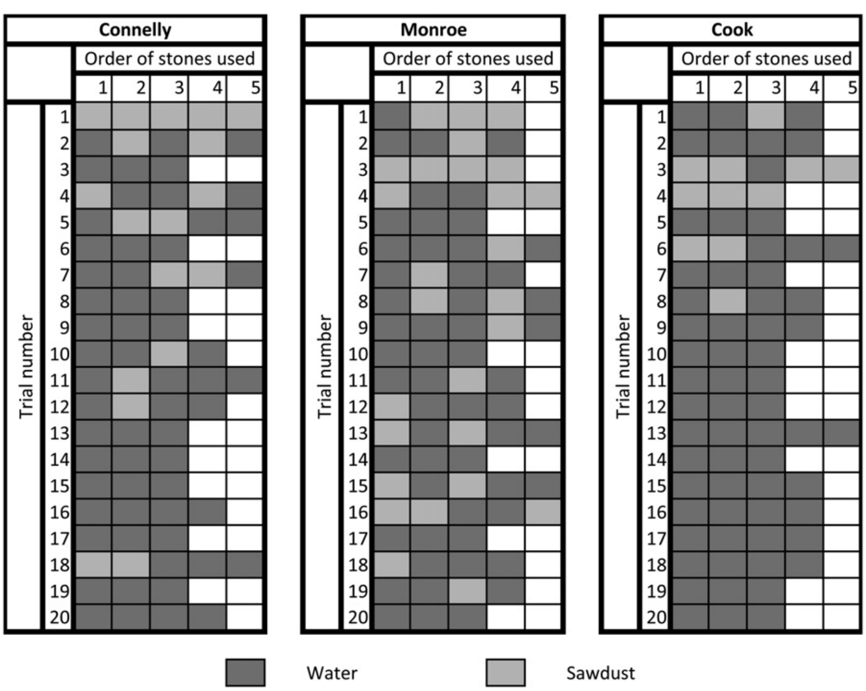

Figure 4. Experiment 3 Trial-by-Trial Description of Behavior

Subjects were successful if they placed at least three stones into the water. (Note that if subjects dropped three stones into the sawdust, they could reach the last stone dropped in and correct their mistake by switching it to the water. Monroe and Cook eventually succeeded on trial 16 and trial 3, respectively, by doing this. Also note that Monroe was not successful on trial 8, because some of the water splashed out of the tube.)

slightly in how far they could reach down into the tube; thus, each subject had a different reachable height. For testing, we lowered the water level by a set amount from the reachable height such that each subject needed to use the same number of stones to be successful regardless of the starting water level.

Procedure

Subjects were tested individually in isolated indoor testing compartments, but they were free to leave into or reenter from an outdoor compartment. These areas were separate from the main aviary. Experiments followed the same general procedure: water was added to the tube to the specified level, and the tube was baited with a waxworm. Although waxworms are semibuoyant, the worm was kept on the water surface by clamping it onto a small cork float. The apparatus was placed onto a shelf in the testing compartment, and the subject was allowed to investigate it for a few seconds before stones were added to the side of the apparatus at the tube base. The trial was ended if the bird successfully retrieved the worm, left the testing compartment, or was unsuccessful after 5 min. The apparatus was then removed. Subjects did not perform the experiments in the same order. Cook performed experiment 1, followed by experiment 2 and then experiment 3. Connelly and Monroe performed experiment 3 first, followed by experiment 2 and then experiment 1. Fry did not complete experiment 1 and thus was not given experiments 2 or 3. The order was varied such that effects of one experiment on another could be accounted for.

Experiment 1

Subjects were given 21 trials, in which the water was presented three times at seven different starting heights requiring a different number of stones to raise the water level to the height that allowed the subject to retrieve the worm. Subjects were provided with ten large stones (mean 14.0 $\pm$ 0.3 g), each of which could raise the water level by 4 mm. Therefore, for each different water level, between one and seven stones were needed to raise the water to the reachable height. For example, if the water level was presented at 4 mm below the reachable height, the subject had to drop only one stone into the tube, whereas if the water level was presented at 28 mm below the reachable height, subjects had to drop seven stones into the tube to be successful. The order of the trials was pseudorandomized such that no more than two trials with the same start height occurred in sequence.

Experiment 2

Subjects were simultaneously given five small stones (2.0 $\pm$ 0.1 g) and five large stones (14.0 $\pm$ 0.5 g) next to the water-filled apparatus. Small stones only raised the water level by 1 mm, whereas large stones raised the water level by 4 mm. In every trial, the water level was presented at 12 mm below the height at which the worm was reachable. Hence, to be successful, subjects could use three large stones or a combination or large and small stones (e.g., two large stones and four small stones). Subjects were given 20 trials each.

Experiment 3

Subjects were presented with two identical tubes spaced 30 cm apart. One tube contained water at 12 mm below the reachable height; the other contained fine sawdust at exactly the same level. Both tubes were baited with a waxworm and cork float. Subjects were given five large stones placed equidistant between the two tubes. Subjects could raise the level of the water by using the stones but could not raise the level of the sawdust. Subjects were given 20 trials each. The position of the tubes was pseudorandomized such that the two tubes were counterbalanced with an equal number of trials on each side and such that the position was not the same for more than two trials in sequence.

Data Analysis

In experiment 1, the number of stones used was compared to the number of stones needed via regression analysis. In experiments 2 and 3, data were analyzed via repeated-measures ANOVA, looking at the effect of trial on the number of stones used of each size or each substrate and the proportion of large to small stones or the proportion of stones dropped in water compared to sawdust. The data were tested for normality such that the model assumptions were met (Anderson Darling test, $p < 0.05$). Alpha was 0.05.

Supplemental Data

Supplemental Data include four movies and can be found with this article online at http://www.cell.com/current-biology/supplemental/S0960-9822(09)01455-9.

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