

Perceptual accuracy and conflicting effects of certainty on risk-taking behaviour

Sharoni Shafir¹, Taly Reich², Erez Tsur¹, Ido Erev² & Arnon Lotem³

The ‘certainty effect’^{1,2} is a notable violation of expected utility theory by decision makers^{3–6}. It shows that people’s tendency to select the safer of two prospects increases when this prospect provides a good outcome with certainty (for example, people prefer a monetary gain of 3 with certainty over 4 with a probability of 0.8, but do not prefer 3 with a probability of 0.25 over 4 with a probability of 0.2). Subsequent work on experience-based decision making in rats⁷ extended the certainty effect to other animals, suggesting its generality across different species and different decision-making mechanisms. However, an attempt to replicate this study with human subjects showed a surprising ‘reversed certainty effect’^{8,9}, namely, the tendency to prefer the safer option decreases when this prospect is associated with certainty (and people now prefer 4 with a probability of 0.8 over 3 with certainty). Here we show that these conflicting results can be explained by perceptual noise and that the certainty effect can be restored experimentally by reducing perceptual accuracy. Using complementary experiments in humans and honeybees (*Apis mellifera*), we show that by manipulating perceptual accuracy in experience-based tasks, both the certainty and the reversed certainty effects can be exhibited by humans and other animals: the certainty effect emerges when it is difficult to discriminate between the different rewards, whereas the reversed certainty effect emerges when discrimination is easy. Our results fit a simple process-based model of matching behaviour^{10,11}, capable of explaining the certainty effect in humans and other animals that make repeated decisions based on experience. This mechanism should probably be distinguished from those involved in the original certainty effect that was exhibited by human subjects in single description-based problems^{1,2}.

Experimental studies of choice behaviour in repeated settings reveal a surprising difference between humans and rats. It has been demonstrated⁷ that rats deviate from the predictions of expected utility theory^{3,4} in the direction of the certainty effect²: their tendency to select the safer of two prospects increases when this prospect provides good outcomes with certainty. Human decision makers exhibit the certainty effect when they make a single choice based on a description of the possible outcomes^{1,2}. However, in repeated choice tasks when the decision makers have to rely on personal experience (like the rats in ref. 7) human subjects exhibit the opposite tendency, namely, the reversed certainty effect^{8,9}. Thus, current data suggest that experience has a different effect on rats than it does on humans and that, paradoxically, experience-based decisions of rats are more similar to human description-based decisions than to experience-based ones.

To resolve this paradox, we hypothesized that these conflicting results represent different experimental conditions. We suspected that rats that received the rewards in the form of cups of water⁷ could assess differences in reward less accurately than humans who received

the rewards in the form of digital numbers^{8,9}. If true, this hypothesis implies that humans, like rats, should exhibit the certainty effect if tested with harder-to-assess rewards. We start with a theoretical illustration showing how a simple experience-based mechanism of choice behaviour can produce the certainty and reversed certainty effects when differences in perceptual accuracy are considered. To test our predictions, we then present complementary experiments in humans and honeybees.

For the theoretical illustration we use the problem studied by ref. 8, which is an experience-based version of the demonstration of the original certainty effect². In this problem, students were asked to choose repeatedly (in 400 trials) between two unmarked buttons of a ‘computerized money machine’. They received no previous information concerning the pay-off distribution of each button, but could learn about it from experience (after each choice the immediate pay-off appeared on the screen, given as numerals representing Israeli currency). Each participant was tested in one of two problems. In problem 1, the R (risky) button provided 4 points with a probability of 0.8 (0 otherwise), whereas the S (safe) button provided 3 points with certainty. In problem 2, all previous probabilities were divided by four, giving R providing 4 with probability 0.2 (0 otherwise), and S providing 3 with probability 0.25 (0 otherwise). Note that because each participant was tested in only one problem, the task was a simple repeated binary choice between two alternatives. Previous studies of such tasks in humans and other animals reveal a robust tendency to deviate from maximization towards matching the probability of future choices to that of past success^{10–12}. The cognitive mechanism of matching behaviour is not fully understood but it is suggested to be based on acquiring a value representation of each alternative that is dynamically adjusted by experience^{10–13}. A decision rule is then applied to determine the action taken in each step based on these representations. A cognitively plausible decision rule for alternatives with variable outcomes has been suggested to be in the form of a competition between samples drawn from the internal representations of each alternative^{14–17}. Accordingly, each alternative is represented in memory by a distribution of expected outcomes (rather than by a single aggregated value); in each step, the decision maker picks a sample from the internal representation of each alternative and chooses the action associated with the most favourable sample.

In Tables 1 and 2 we show how applying this mechanism to the above set of problems results in the reversed certainty effect when discrimination is easy (Table 1), and in a behaviour that resembles the original certainty effect when discrimination is difficult (Table 2). Table 1 considers the extreme case of perfect discrimination. Under the specified choice mechanism, the proportion of R choices in problems 1 and 2 should reflect the proportion of cases in which a sample picked from the representation of R is greater than that picked from

¹B. Triwaks Bee Research Center, Department of Entomology, Faculty of Agricultural, Food and Environmental Quality Sciences, The Hebrew University of Jerusalem, Rehovot 76100, Israel. ²Max Wertheimer Minerva Center for Cognitive Studies, Faculty of Industrial Engineering and Management, Technion, Haifa 32000, Israel. ³Department of Zoology, Faculty of Life Sciences, Tel-Aviv University, Tel-Aviv 69978, Israel.

Table 1 | Expected proportion of R choices when discrimination is easy

Problem 1			
		R	
	Pay-offs and probabilities	4 ($P = 0.8$)	0 ($P = 0.2$)
S	3 ($P = 1$)	R is best ($P = 0.8$)	S is best ($P = 0.2$)
	0 ($P = 0$)	–	–
Proportion of R choices: 0.8			
Problem 2			
		R	
	Pay-offs and probabilities	4 ($P = 0.2$)	0 ($P = 0.8$)
S	3 ($P = 0.25$)	R is best ($P = 0.05$)	S is best ($P = 0.2$)
	0 ($P = 0.75$)	R is best ($P = 0.15$)	No difference ($P = 0.6$)
Proportion of R choices: $0.05 + 0.15 + 0.6 \times 0.5 = 0.5$			

Calculation of the expected proportion of R choices in problems 1 and 2, when discrimination is easy and R is chosen when perceived as the best alternative. When there is no perceived difference, R and S are chosen at random (each with a probability of 0.5).

the representation of S. If the internal representations reflect past experiences accurately, the probability of such cases can be derived directly from the distribution of joint pay-offs described in Table 1. It is easy to see from Table 1 that, under these conditions, the proportion of R choices should be 0.8 in problem 1 but only 0.5 in problem 2. This implies a strong preference for the risky alternative when the safer alternative provides good outcomes with certainty, namely, a strong reversed certainty effect^{8,9}. Note that the strength of this result depends critically on the frequency of cases in which a sample of 4 competes with a sample of 3 (Table 1; top-left cell of the four ‘inner’ cells). This is most common in problem 1, but extremely rare in problem 2 (0.8 versus 0.05). Furthermore, the assumption of a complete dominance of 4 over 3 is based on the assumption of perfect perception and memory. Clearly, errors that cause 4 to be perceived (or remembered) as similar to 3 should diminish the preference of the risky alternative in problem 1, thereby attenuating the reversed certainty effect. If discrimination becomes so difficult that subjects can tell the difference between zero and 3 (or zero and 4), but not between 3 and 4, the strong reversed certainty effect is replaced by a weak certainty effect (Table 2, 0.4 R choices in problem 1; that is, subjects are expected to shift towards risk aversion). The perceptual constraints assumed in Table 2 may be considered simply as poor perceptual resolution, or also as an extreme case of the Weber–Fechner law¹⁸, according to which diminishing sensitivity to increasing magnitudes can increase perceptual noise. Theoretically, it can also emerge from a sharply concaved subjective value function that increases sharply from zero to 3 but remains virtually the same between 3 and 4. Finally, we remark that qualitatively similar results are expected from realistically refined versions of the above mechanism in which some level of averaging is involved in shaping the distribution of expected outcomes in memory representation: for example, when 4 is remembered as less than its perceived value because it is also associated with experiencing zeros at the same key. Such devaluation of the risky alternative would make it more susceptible to perceptual noise, allowing the certainty effect to emerge even if a reward of 4 was never perceived as equal to 3 but only close to it. Conversely, a tendency to underweight rare events (zero pay-offs) may increase the preference for the risky alternative, producing a reversed certainty effect that may be stronger than expected from Table 1. As long as zero is clearly distinguishable from 3, difficult discrimination between 3 and 4 reduces the attractiveness of the risky option whereas easy discrimination increases it.

Table 2 | Expected proportion of R choices when discrimination is difficult

Problem 1			
		R	
	Pay-offs and probabilities	4 ($P = 0.8$)	0 ($P = 0.2$)
S	3 ($P = 1$)	No perceived difference ($P = 0.8$)	S is best ($P = 0.2$)
	0 ($P = 0$)	–	–
Proportion of R choices: $0.8 \times (0.5) = 0.4$			
Problem 2			
		R	
	Pay-offs and probabilities	4 ($P = 0.2$)	0 ($P = 0.8$)
S	3 ($P = 0.25$)	No perceived difference ($P = 0.05$)	S is best ($P = 0.2$)
	0 ($P = 0.75$)	R is best ($P = 0.15$)	No difference ($P = 0.6$)
Proportion of R choices: $0.05 \times 0.5 + 0.15 + 0.6 \times 0.5 = 0.475$			

Calculation of the expected proportion of R choices in problems 1 and 2, when discrimination is difficult (3 and 4 are indistinguishable) and R is chosen when perceived as the best alternative. When there is no perceived difference, R and S are chosen at random (each with a probability of 0.5).

If our proposed mechanism is correct, it should be possible to produce the certainty and the reversed certainty effects experimentally, in both humans and other animals, by manipulating the level of perceptual accuracy in the presentation of rewards. To test this prediction with human subjects we carried out a set of experiments in which we replicated the experimental set-up of ref. 8, but replaced the clear feedback of digital numbers with patches of red dots representing the amount of reward (see Methods and Fig. 1). The results were striking. When the same rewards of 3 and 4 monetary units were presented by random patches of 30 and 40 dots, respectively, the reversed certainty effect was replaced by the original certainty effect (compare Fig. 1a with b). This result cannot be explained by the mere use of dots, because in a second experiment, when the same number of dots was presented in a more regular manner (Fig. 1c), the certainty effect diminished considerably. It would seem that the regular presentation of dots (Fig. 1c) makes discrimination easier than in the random patch condition (Fig. 1b), but not to the extent that will produce the reversed certainty effect (as in Fig. 1a). Finally, a third experiment (Fig. 1d) shows that the presentation of rewards in patches of dots can still produce the reversed certainty effect provided that the difference between the two rewards is sufficiently large to facilitate easy discrimination (30 versus 60 dots).

To test our predictions with an animal model, we carried out a set of experiments with honeybees (*Apis mellifera*) that were trained to choose between two syringe tips from which rewards with different sugar concentrations or no reward (empty tip) were provided. The probabilities of receiving a reward (sugar solution) or no reward in the certain and risky alternatives were the same as in problems 1 and 2. To manipulate perceptual accuracy we provided the high and low rewards (analogous to 4 and 3 in the human set-up) as sugar concentrations of 10% and 5% (easy discrimination), 6.7% and 5% (medium discrimination), and identical 6.7% concentrations (impossible discrimination). The results were highly consistent with our predictions and with the human data. We found a strong reversed certainty effect when discrimination was easy (Fig. 2a), a medium reversed certainty effect when discrimination was medium (Fig. 2b), and a weak certainty effect when discrimination was impossible (Fig. 2c). Note that in the case of medium discrimination, the expected values of the two options were virtually the same ($0.8 \times 6.7\% = 5.3\% \approx 5\%$) and yet, a significant reversed certainty

effect was clearly indicated (Fig. 2b). This strong effect cannot be attributed to the ability of honeybees to discriminate between expected values of 5% and 5.3% because honeybees show a weaker effect in a much simpler discrimination test between constant rewards of 5% and 6.7% (reported in the legend to Fig. 2). The risk indifference observed in all discrimination conditions of problem 2 is also inconsistent with expected utility theory (especially in Fig. 2a where discrimination was easy and the expected value of the risky option was clearly higher), but was predicted by Tables 1 and 2. Finally, because the certainty effect exhibited by the honeybees in the present study (Fig. 2c) was expected to be weak (see Table 2), it is not surprising that it failed to reach statistical significance. There is good experimental evidence, however, that honeybees are strongly

risk averse when the differences between certain and risky alternatives are more pronounced¹⁹.

In light of our experimental results, previous conflicting evidence⁷⁻⁹ can be resolved by the simple assertion that humans and other animals deviate from maximization towards a preference for the alternative perceived to lead to better outcomes most of the time (thereby underweighting rare events⁹). This tendency leads to the reversed certainty effect when discrimination is easy, and to behaviour that resembles the original certainty effect when

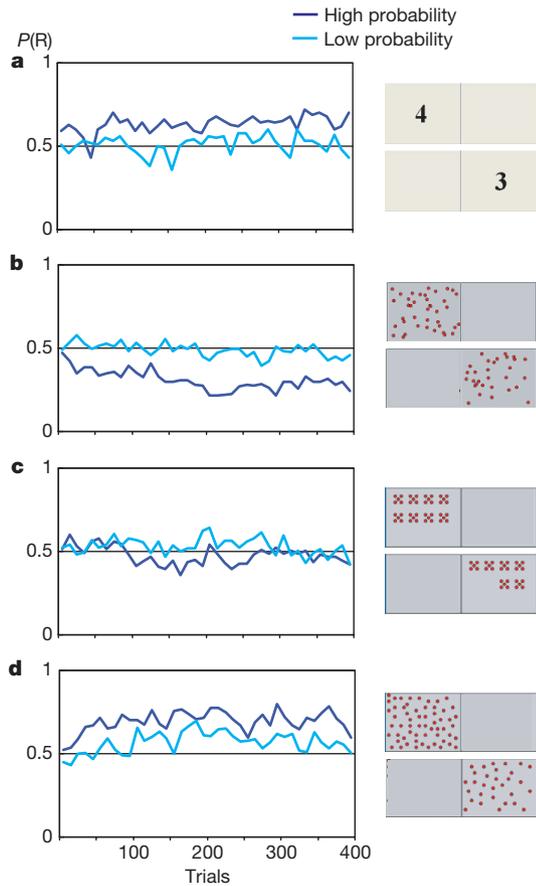


Figure 1 | Experiments with human subjects. Average proportion of human subjects' selection of the risky alternative (R) in 400 trials (presented in 40 blocks of 10 trials) when the safe alternative (S) provides reward with certainty (dark blue line: problem 1, high probability condition), and after both probabilities of receiving reward (for S and R) were divided by four (light blue line: problem 2, low probability condition). A typical reward feedback in each experiment is shown to the right of each panel. **a**, The original reversed certainty effect⁸ (problems 1 and 2 as in Table 1) and feedback given as numeral digits representing rewards in 0.01 new Israeli shekels (the difference between problems was significant⁸). **b**, The same set-up and problems as **a** but feedbacks given as random patches of 30 and 40 dots. (The original certainty effect is restored: $P = 0.001$, Mann-Whitney U -test, $z = 3.27$, $n_1 = n_2 = 30$.) **c**, Same as **b** but the 30 and 40 dots are organized in groups ($P = 0.093$, Mann-Whitney U -test, $z = 1.68$, $n_1 = n_2 = 20$). **d**, Dots feedback as in **b** but problems 1 and 2 are modified by increasing the reward difference between S and R, represented by 30 and 60 dots, respectively (the difference between problems is significant and in the direction of the reversed certainty effect, $P = 0.007$, Mann-Whitney U -test, $z = 2.69$, $n_1 = n_2 = 20$). Statistical differences between participants' proportion of R choices in problems 1 and 2 were tested using a two-tailed non-parametric Mann-Whitney U -test (using Statistica version 6.0). Except for **a**, which is based on ref. 8, all data in **b-d** are original and are not reported elsewhere.

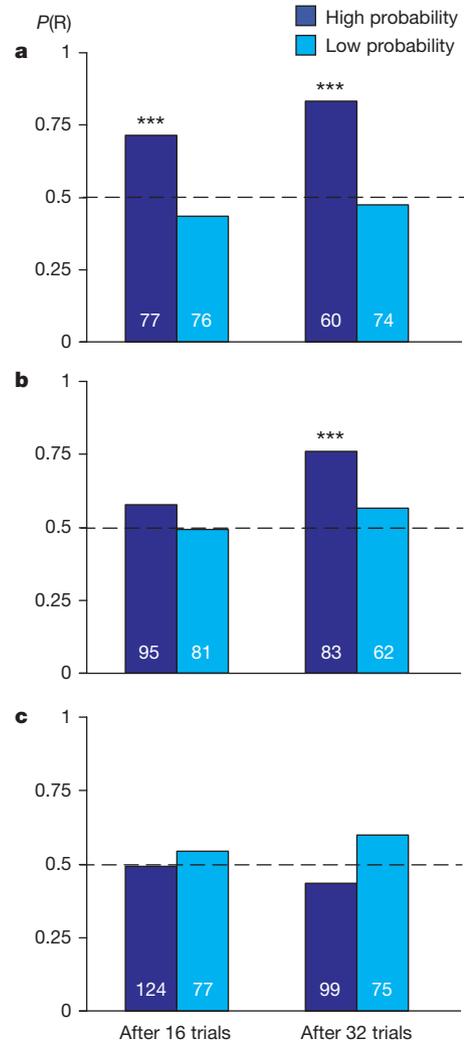


Figure 2 | Experiments with honeybees. The proportion of honeybees that chose the risky alternative (R) after 16 and 32 conditioning trials in the high probability conditions of problem 1 (high probability, dark blue bars: the safe alternative provides reward with certainty and the risky alternative with a probability of 0.8), and in the low probability conditions of problem 2 (low probability, light blue bars: after both probabilities were divided by four), when discrimination between the riskier and safer rewards was easy (**a**; 10% versus 5% sugar concentration), medium (**b**; 6.7% versus 5% sugar concentration) and impossible (**c**; 6.7% versus 6.7% sugar concentration). The dashed line marks risk indifference (that is, $P(R) = 0.5$). Numbers in bars are sample sizes. Three asterisks indicate highly significant deviation from risk indifference (χ^2 test, degrees of freedom = 1 (χ_1^2), $P \leq 0.0001$), whereas unmarked bars show no significant deviation from risk indifference. A control experiment (not shown) confirmed that honeybees were able to discriminate well between a 5% sugar solution and a drop of water (choice proportions after 16 and 32 conditioning trials were 0.78 ($N = 36$, $\chi_1^2 = 11.8$, $P = 0.0006$) and 0.77 ($N = 31$, $\chi_1^2 = 9.9$, $P = 0.0017$), respectively), and could also discriminate, but less well, between 6.7% and 5% sugar solutions (choice proportions after 16 and 32 conditioning trials were 0.61 ($N = 82$, $\chi_1^2 = 4.0$, $P = 0.046$) and 0.64 ($N = 55$, $\chi_1^2 = 11.8$, $P = 0.0006$), respectively).

discrimination between the two attractive rewards is difficult. We emphasize that this latter case may only appear to resemble the original certainty effect, because our study suggests that the similarity to the original certainty effect is in fact misleading. The mechanism considered in our study is relevant to experienced-based decisions, and can produce the observed certainty effect only when perceptual noise is involved. This was clearly not the case in the original paradox¹ and its reformulation by ref. 2, where subjects made a single choice based on an accurate description of possible outcomes. Notably, a recent study of the original description-based Allais-type problem showed that the introduction of a certainty reference has a marked effect on decision-makers' brain activation²⁰. In other words, the original certainty effect seems to be associated with a strong response to the presentation of the concept of certainty. In experience-based tasks, on the other hand, the concept of certainty is never presented to the participants. The knowledge that one alternative is certain can only be inferred indirectly after many repeated choices (and may be acquired much more easily when the subjects are forced to sample each alternative separately²¹). It is therefore quite unlikely that the same type of brain activation responsible for the original certainty effect is also responsible for the certainty effect found in our study (although it might have only activated after many trials, when some sense of certainty could be acquired, and contributed to the increasing effect of certainty observed in Fig. 1b after about 200 trials). Considering all of the above, both the certainty and the reversed certainty effects studied here seem to represent a robust and independent violation of expected utility theory, which is specific to repeated-choice behaviour. We suggest calling this phenomenon 'perceptual matching' because it is derived from matching choices to the perceived best option in memory representation. Considering the prevalence of repeated choices in real life situations, this phenomenon may be as important as the original (but different) certainty effect that inspired its discovery.

METHODS SUMMARY

Experiments with human subjects were based on paid participants (students) that received 20 new Israeli shekels for showing up and contingent pay-off in 400 repeated choices between alternatives of problems 1 and 2 (that is, 0.04 new Israeli shekels with a probability of 0.8 versus 0.03 new Israeli shekels with certainty, and 0.04 new Israeli shekels with a probability of 0.2 versus 0.03 new Israeli shekels with a probability of 0.25, respectively). To generate perceptual difficulty, the pay-off obtained after each choice was presented on the computer screen in the form of red dots rather than numerical digits (see Fig. 1). No previous information on pay-off structure or length of experiment was provided to participants.

Three experiments with honeybees were conducted to test the effect of perceptual accuracy on a similar set of problems as with human subjects. The pay-off obtained after each choice was a 2- μ l drop of sucrose solution of different concentrations. The reward 0 was represented by an empty syringe tip. In the first experiment (Fig. 2a), the pay-off in the risky and safe alternatives was 10% and 5% sugar concentration, respectively. In the second experiment (Fig. 2b), pay-off was 6.7% and 5%, and in the third experiment (Fig. 2c), the pay-off in both

alternatives was 6.7%. Owing to differences in sensitivity to sucrose between nectar- and pollen-collecting honeybees²², only foragers with full pollen baskets were captured, on their return to the hive. Honeybees were tested in a binary-choice proboscis-extension-response conditioning assay¹⁹. There were 32 conditioning trials with test trials after trials 16 and 32, in which both odours were presented for 1 s twice, in an alternating sequence.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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METHODS

Experiments with human subjects. Undergraduate students served as paid participants in the experiments (30 were assigned to each problem in the first experiment and 20 to each of the problems in the other experiments). In addition to the performance-contingent pay-off described below, each student received 20 new Israeli shekels for showing up. The total pay-off ranged from 23 to 37 new Israeli shekels (1 new Israeli shekel \approx 0.22 US dollars).

Three experiments were conducted to test the effect of perceptual accuracy on the set of problems studied by refs 2 and 8 (that is, R versus S: in problem 1, 4(0.8) versus 3(1); in problem 2, 4(0.2) versus 3(0.25)). To generate perceptual difficulty, the pay-off obtained after each choice was presented in the form of red dots rather than numerical digits (see Fig. 1). In the first experiment (Fig. 1b) the numerical feedback of 3 and 4 was replaced by patches of 30 and 40 red dots. The location of each dot in a patch was randomly assigned at each trial. The reward 0 was represented by a single white dot in the centre of the display area. The second experiment (Fig. 1c) resembled the first one but, in order to improve perception, the 30 and 40 dots were organized into regular groups of five dots. In the third experiment, the feedback was the same as in the first experiment (patches of randomly distributed red dots) but problems 1 and 2 were modified to increase the difference between favourable outcomes from 30 and 40 to 30 and 60 dots, respectively (Fig. 1d: problem 1, 60(0.8) versus 30(1); problem 2, 60(0.2) versus 30(0.25)).

The task in all experiments was a binary choice between two button keys on a computer screen, followed by an immediate feedback that appeared for one second on the surface of the selected key. After this second, the selected key returned to its original state and the feedback reappeared at the centre of a display panel located just below the two keys until the next key was selected. The participants repeated this task 400 times, and usually completed the experiment within 10 to 30 min. They were informed that they were playing on a 'computerized dot machine', and that each dot signified a pay-off of 0.001 new Israeli shekels. They received no previous information as to the game's pay-off structure, and to avoid an 'end of task' effect, they were not informed that the experiment would comprise 400 trials. The time interval between repeated choices was determined by the participants, but was too short to enable counting of the dots (and the participants reported that they never tried to do so).

Experiments with honeybees. Three experiments were conducted to test the effect of perceptual accuracy on a similar set of problems as with human subjects. The pay-off obtained after each choice was a 2- μ l drop of sucrose solution of different concentrations. The reward 0 was represented by an empty syringe tip. In the first experiment (Fig. 2a), the pay-off in the risky and safe alternatives was 10% and 5% sugar concentration, respectively. In the second experiment (Fig. 2b) pay-off was 6.7% and 5%, and in the third experiment (Fig. 2c), the pay-off in both alternatives was 6.7%.

Owing to differences in sensitivity to sucrose between nectar- and pollen-collecting honeybees²², only foragers with full pollen baskets were captured, on their return to the hive. Honeybees were tested in a binary-choice proboscis-extension-response conditioning assay¹⁹. For each subject, an odour (benzyl acetate or geranyl acetate) was presented from either left or right and associated with either R or S pay-offs. The other odour was presented from the other side and associated with the other pay-off, in a balanced design across subjects. During conditioning trials, a harnessed honeybee was presented with an odour for 5 s. Pay-off was delivered 3 s after initiation of odour. There were 32 conditioning trials, with an inter-trial interval of 12 or 15 min (for the low- and high-probability conditions, respectively). Inter-trial interval was smaller in the low-probability condition because the probability of being fed was smaller. A test trial was conducted after trials 16 and 32, in which both odours were presented for 1 s twice, in an alternating sequence. A photograph of the honeybee was then taken. Photographs were scored blindly for the direction in which the honeybee extended its proboscis, which represented its choice¹⁹.

An automated proboscis-extension-response conditioning machine was used, consisting of a carousel loaded with 24 honeybees mounted on a stepper motor. Miniature pumps controlled delivery of odours. Hydraulic arms brought the appropriate syringe tip above the honeybee and lowered it towards the honeybee's antennae and proboscis. Syringe pumps administered sugar solution of the appropriate concentration. Image analysis software monitored the size of the drop on the syringe tip before each delivery.