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P. S. Blackawton[1], S. Airzee[1], A. Allen[1], S. Baker[1], A. Berrow[1], C. Blair[1], M. Churchill[1], J. Coles[1], R. F.-J. Cumming[1], L. Fraquelli[1], C. Hackford[1], A. Hinton Mellor[1], M. Hutchcroft[1], B. Ireland[1], D. Jewsbury[1], A. Littlejohns[1], G. M. Littlejohns[1], M. Lotto[1], J. McKeown[1], A. O'Toole[1], H. Richards[1], L. Robbins-Davey[1], S. Roblyn[1], H. Rodwell-Lynn[1], D. Schenck[1], J. Springer[1], A. Wishy[1], T. Rodwell-Lynn[1], D. Strudwick[1] and R. B. Lotto[2,*]

[1]*Blackawton Primary School, Blackawton, Devon, UK*
[2]*Institute of Ophthalmology, University College London, 11-43 Bath Street, London EC1V 9EL, UK*
**Author for correspondence (lotto@ucl.ac.uk).*

Background*: Real science has the potential to not only amaze, but also transform the way one thinks of the world and oneself. This is because the process of science is little different from the deeply resonant, natural processes of play. Play enables humans (and other mammals) to discover (and create) relationships and patterns. When one adds rules to play, a game is created. This is science: *the process of playing with rules that enables one to reveal previously unseen patterns of relationships that extend our collective understanding of nature and human nature*. When thought of in this way, science education becomes a more enlightened and intuitive process of asking questions and devising games to address those questions. But, because the outcome of all game-playing is unpredictable, supporting this 'messyness', which is the engine of science, is critical to good science education (and indeed creative education generally). Indeed, we have learned that doing 'real' science in *public spaces* can stimulate tremendous interest in children and adults in understanding the processes by which we make sense of the world. The present study (on the vision of bumble-bees) goes even further, since it was not only performed outside my laboratory (in a Norman church in the southwest of England), but the 'games' were themselves devised in collaboration with 25 8- to 10-year-old children. *They* asked the questions, hypothesized the answers, designed the games (in other words, the experiments) to test these hypotheses and analysed the data. *They* also *drew* the figures (in coloured pencil) and wrote the paper. Their headteacher (Dave Strudwick) and I devised the educational programme (we call 'i,scientist'), and I trained the bees and transcribed the childrens' words into text (which was done with smaller groups of children at the school's local village pub). So what follows is a novel study (scientifically and conceptually) in '*kids speak*' without references to past literature, which is a challenge. Although the historical context of any study is of course important, including references in this instance would be disingenuous for two reasons. First, given the way scientific data are naturally reported, the relevant information is simply inaccessible to the literate ability of 8- to 10-year-old children, and second, the true motivation for any scientific study (at least one of integrity) is one's own curiousity, which for the children was not inspired by the scientific literature, but their own observations of the world. This lack of historical, scientific context does not diminish the resulting data, scientific methodology or merit of the discovery for the scientific and 'non-scientific' audience. On the contrary, it reveals science in its truest (most naive) form, and in this way makes explicit the commonality between science, art and indeed all creative activities.

***Principal finding*: 'We discovered that bumble-bees can use a combination of colour and spatial relationships in deciding which colour of flower to forage from. We also discovered that science is cool and fun because you get to do stuff that no one has ever done before. (Children from Blackawton)'.**

Keywords: *Bombus terrestris*; buff-tailed bumble-bee; visual perception; colour vision; behaviour

1. INTRODUCTION

(a) *Once upon a time* ...

People think that humans are the smartest of animals, and most people do not think about other animals as being smart, or at least think that they are not as smart as humans. Knowing that other animals are as smart as us means we can appreciate them more, which could also help us to help them.

Scientists do experiments on monkeys, because they are similar to man, but bees could actually be close to man too. We see bees in the natural habitat doing what they do, but you do not really see them doing human things—such as solving human puzzles like Sudoku. So it makes you wonder if they could solve a human puzzle. If they could solve it, it would mean that they are really smart, smarter than we thought before, which would mean that humans might have some link with bees. If bees are like us in some way, then understanding them could help us understand ourselves better.

To get ready to do the experiments with the bees we first talked about science being about playing games and making puzzles. We then got into groups and made up games to play using random pieces of physical education equipment. This gave us experience of thinking of games and puzzles. We then had to explain our games to other people. After talking about what it is like to create games and how games have rules, we talked about seeing the world in different ways by wearing bug eyes, mirrors and rolled-up books. We then watched the David Letterman videos of 'Stupid Dog Tricks', in which dogs were trained to do funny things. Next, we too had to learn to solve a puzzle that Beau (a neuroscientist) and Mr Strudwick (our headteacher) gave us (which took an artificial brain 10 000 trials to solve, but only four for us). Afterwards, we started asking questions about bees, and then more specific questions about seeing colour using the bee arena (figure 1).

We came up with lots of questions, but the one we decided to look at was whether bees could learn to

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(*a*)

(*b*)

(*c*)

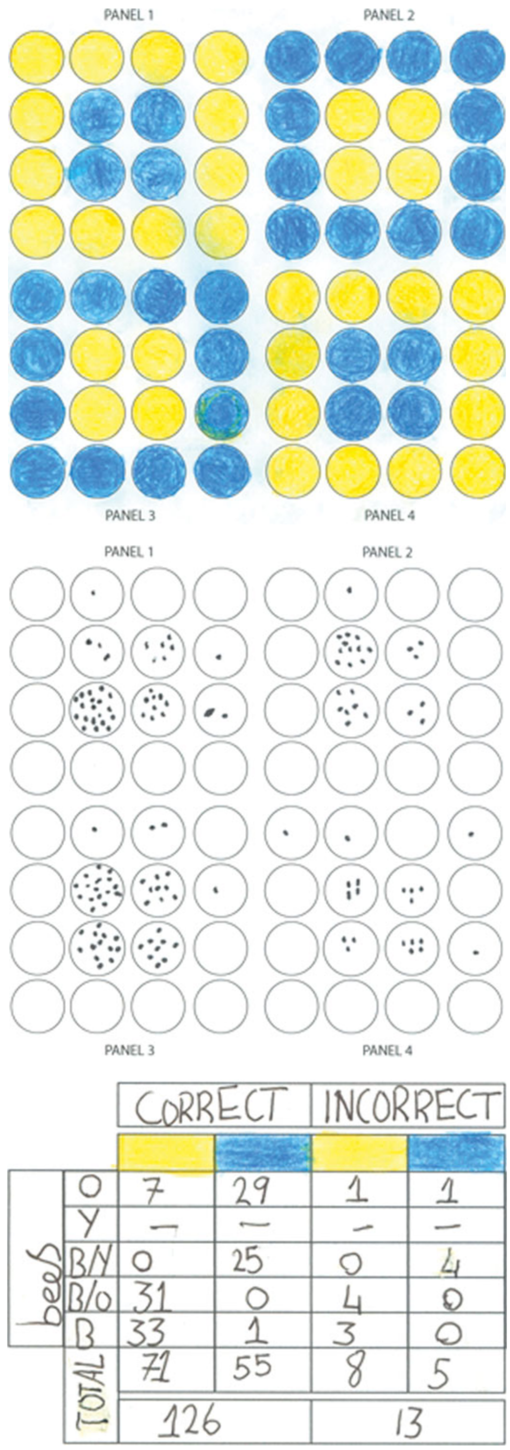


Figure 1. Conditions and responses to 'test 1' (control). (*a*) The pattern of colours that the bees were trained to and tested on in their first test (see text for explanation). (*b*) The selections made by all the bees tested (dots show where each bee landed and tried to get sugar water). (*c*) A table showing the preferences of each bee during testing (see text for explanation).

use the spatial relationships between colours to figure out which flowers had sugar water in them and which had salt water in them. It is interesting to ask this question, because in their habitat there may be flowers that are bad for them, or flowers from which they might already have collected nectar. This would mean that it is important for bees to learn which flower to go to or to avoid, which would need them to remember the flowers that were around it, which is like a puzzle.

To test this we gave the bees a series of challenges to see if they could complete them or not, and then tested them to see if they solved the puzzle and how they solved it. It was a difficult puzzle, because the bees could not just learn to go to the colour of the flower. Instead, they had to learn to go to one colour (blue) *if* it was surrounded by the opposite colour (yellow), but also to go to the opposite colour (yellow) if it was surrounded by blue. We also wanted to know if all the bees solved the puzzle in the same way. If not, it would mean that bees have personality (if a bee goes to the blue flower every time, it tells us that it really likes blue).

2. MATERIAL AND METHODS

(a) *The bee arena*

The bee arena, which was made out of Plexiglas, had six sides. The arena was 1 m high, 1 m wide and 1 m deep, and two of the side panels had three doors each. It had a vertical lightbox at the end opposite the side through which the bees entered by a small hole. The lightbox was made out of aluminium, with a Plexiglas screen in front of the six fluorescent lights. An aluminium cross was placed in front of the Plexiglas screen, and this cross had grooves in its sides so that we could slide four black aluminium panels into the cross. Each panel had 16 cut-out circular holes in four rows of four circles each. Each circle was 8 cm in diameter. The holes were covered by the Plexiglas screen. In the centre of each circle was a Plexiglas rod with a small hole in the middle in which we put sugar water, salt water or nothing. Behind each hole there were slits so that squares of coloured gel filters could be slotted in, making the light shining through each hole coloured. It was like putting a piece of coloured see-through paper on a light to let the colour of the paper shine through.

(b) *The bees*

The bees had black and yellow stripes with white bottoms. The type of bee was *Bombus terrestris*. The beehive was delivered from Koppert (UK).

(c) *Training phase 1*

To teach the bees to go to the Plexiglas rods as if they were flowers, all the circles in every panel were kept white, and all the rods had sugar water in them. Once the labelled foragers learned that the flowers contained a reward, which took four days, we marked the bees, and then set up the puzzle.

(d) *Marking bees*

We let the foragers into the arena and turned the lights off, which made the bees stop flying (because they do not want to fly into anything). We picked the bees up with bee tweezers and put them into a pot with a lid. We then put the tube with the bees in it into the school's fridge (and made bee pie ☺). The bees fell asleep. Once they fell asleep, we took the bees out, one at a time, and painted little dots on them (yellow, blue, orange, blue-orange, blue-yellow, etc.). We put them into the tube and warmed them up and then let them into the arena. No bees were harmed during this procedure.

(e) *Training phase 2 ('the puzzle' . . . duh duh duuuuhhh)*

We set up a puzzle for the bees as in the following. Imagine having a panel with 16 circles, with a large square of 12 yellow circles on the outside and a small square of four blue circles in the middle. This was the case for two panels, but the other two panels were the opposite, and instead of yellow on the outside as the larger square and blue on the inside as the smaller square, we had blue on the outside and yellow on the inside. The sugar reward (1 : 1 with water) was only in the middle four flowers inside each panel of 16 flowers. Every 10–40 min, we swapped the locations of the panels around the different quadrants so that the bees could not learn the locations of the rewarding flowers. We also cleaned the Plexiglas stems so that the bees could not use scent to tell the other bees that flower had the reward. Instead they had to learn: if there was blue on the outside ring of each panel of 16 circles, then they had to go to the inner four yellow circles. If, however, there was yellow on the outside ring, then they had to go to the inner four blue circles. During the first 2 days of training, sugar water was placed only in the four middle flowers in each panel and nothing in the outside ring (so that they would get the hang of it). During the second 2 days we added salt water to the flowers in the outside rings. We did this so that they would learn not to go just to the colours, but had to learn the pattern. Otherwise they might fail the test, and it would be a disaster. After training, we tested the bees to see if they solved the puzzle.

(f) *Testing the bees*

We tested the bees using the same pattern of colours, but without sugar water or salt water, to see which flowers they would go to. We also moved the locations of the panels so that the layout was different from when they were just trained. We let the labelled foragers into the arena one at a time so that they would not copy each other (as humans might). We tracked their flower choices using a sheet of paper with the 64 circles marked into the four quadrants. Whenever the bees landed on a flower and stuck their tongue (proboscis) into the Plexiglas rod, we would mark the matching circle on the sheet. We marked each circle with a '1', a '2' or a '3' and so on, to track where they went to see how their behaviour might have changed with time. After a while, the bees might have got annoyed because they were not getting a reward, and might have started making mistakes or searching randomly. So we let each forager make only around 30 choices before stopping the test. Each bee was tested three times (see §3).

3. RESULTS

After training the bees in the arena, we tested them three times to see if they had learned anything during training.

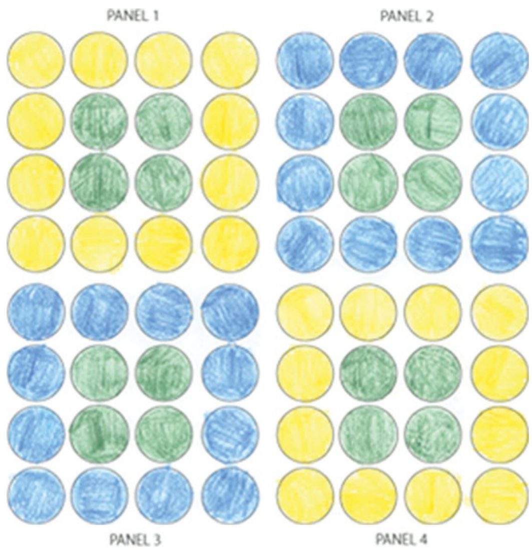
(a) *Test 1 (the control)*

In the first test the bees were given the same pattern we had trained them with. After training, we moved the colours of the panels clockwise once, so that the colours of the quadrants would be different for the bees, and they could not just go to the same place as last time to get a reward (see figure 1*a* for a hand drawing of the test). If the bees had solved the puzzle, they should land on the flowers in the middle of each quadrant and stick their tongues (proboscis) in the flower, as during training this is how they would have had a reward (during the test, they did not get a reward).

Figure 1*b* shows where four of the bees went during the test (unfortunately, one of the bees (called 'yellow') did not come out of the hive during this test). Each dot in figure 1*b* is an attempted forage. The figure shows that the bees went to the middle flowers 126 times, and to the outside flowers in the four quadrants a total of 13 times (see 'total' in figure 1*c*). So, out of 139 attempted forages, 90.6 per cent were to correct flowers (correct means flowers that would have had sugar water during training).

Figure 1*c* shows how many times each individual bee went to correct and incorrect blue and yellow flowers. We did this so that it would be clearer to see where each bee went during the test. 'Orange' (O) bee selected seven correct (middle) yellows and only one incorrect (outside) yellow. She also went to 29 correct blue and only one incorrect blue. This bee prefers blue in the middle, but also prefers yellow in the middle. This bee did extremely well, because it went to both colours at correct locations in the flowers. 'Blue/yellow' (B/Y) bee went to neither outside yellow flowers nor middle yellow flowers. Instead it went to 25 correct blue flowers (middle) and only four incorrect blue flowers (outside). So this bee preferred blue to yellow. The 'Blue/Orange' (B/O) bee went to 31 correct yellow flowers and four incorrect yellow flowers, and never went to blue flowers. The 'Blue' (B) bee went to 33 correct yellow flowers and only three incorrect yellow flowers, and selected the correct blue flowers only once. These results are shown in figure 1*c*. We conclude that one bee went to a mixture of colours in the correct locations, but the rest preferred one colour over the other. However, although they preferred one colour, they only went to the middle of the panel that had that colour (as this is the flower that would have had a reward). This test shows that altogether the bees solved the puzzle very well, as their choices collectively were divided between all blue and yellow *rewarding* flowers. We then presented the bees with two more tests to see how they solved the puzzle they were trained for.

(a)



(b)

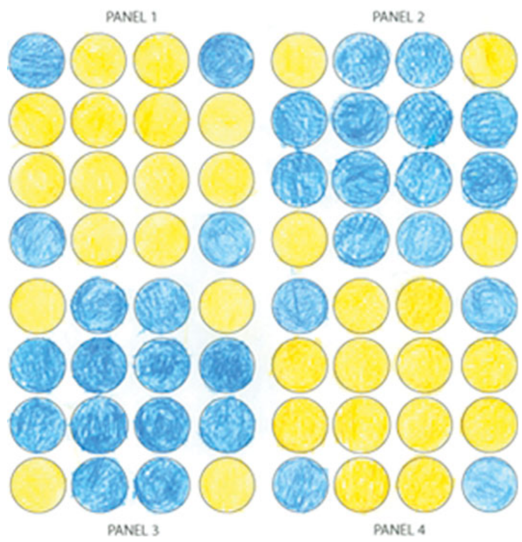
BEES	MIDDLE (green)	SURROUND (yellow)	SURROUND (blue)
O	3	4	23
Y	4	11	5
B/Y	0	21	0
B/O	12	0	8
B	15	1	3
TOTAL	34	37	39
TOTAL	34	76	

Figure 2. Conditions and responses to 'test 2'. (*a*) The pattern of colours that the bees were tested on in their second test (see text for explanation). (*b*) A table showing the preferences of each bee during test 2 (see text for explanation).

(b) *Test 2 (the first experiment)*

Test 2 was very similar to test 1, except that the middle flowers in each quadrant were green. We did this to see whether the bees learned to go to the colours or to the location of the rewarding flowers during training. If the bees learned to go to the location of the rewarding flowers, then they should land on the green flowers in test 2. See figure 2*a* for a hand drawing of this test.

(*a*)



(*b*)

	CORNERS (yellow)	CORNERS (blue)	NOT-CORNERS (yellow)	NOT-CORNERS (blue)
BEES O	2	5	15	4
Y	5	3	13	8
B/Y	2	16	0	18
B/O	17	0	13	1
B	11	0	14	0
TOTAL	37	22	55	31
	59		86	

Figure 3. Conditions and responses to 'test 3'. (*a*) The pattern of colours that the bees were tested on in their third test (see text for explanation). (*b*) A table showing the preferences of each bee during test 3 (see text for explanation).

Figure 2*b* shows a table of the choices made by the bees during this test. In total, the bees went to the green middle flowers only 34 times, and to the outside blue and yellow flowers 76 times (see total in figure 2*b*). So, out of 110 attempted forages, 30.9 per cent were to the middle flowers. If the bees were guessing, they should have selected the green flowers 25 per cent of the time, which is very close to 30 per cent. So we conclude that the bees did not solve test 1 by only going to the middle flowers of each quadrant ('dah dahhh dahhhhhh'). However, two of the bees (labelled B/O and B) went most often to the green, middle flowers. So they seemed to have learned a different rule to the other three bees.

(c) *Test 3 (the second experiment)*

In the third test, instead of having large squares of yellow and blue around the outside of each panel, and a smaller square of yellow and blue on the inside of each panel, we took the four inside flowers and put them in the corners of each panel. See figure 3*a* for a hand drawing of what this test looked like. We did this because we wanted to see if the bees solved test 1 by learning during training to go to the colours of each panel that were fewest in number. We could also see if they still preferred to go only to the middle flowers. If the bees had learned to go to flowers that were fewest in each panel, then they should go to the flowers in the corners.

The table in figure 3*b* shows where all five bees went during the test. You can see that the bees as a group went to the corner flowers 59 times, and to the 'not-corners' 86 times (see 'total' in figure 3*b*). So, out of 145 attempted forages, 40.1 per cent were to the corners. This is very different from what they did in test 1. When the same flowers were not in the corners but in the middle as in test 1, they selected them 90.6 per cent of the time, which is 2.2 times more often. We think that the bees in test 3 selected the flowers randomly, and conclude that the bees did not learn to go to the flowers that had the fewest colours in each panel. Also, this time, the B and B/O bees did not prefer the middle flowers in each panel. This means that in test 2 they must have used the larger square of blue and yellow flowers to decide to forage from the *middle* green flowers.

4. DISCUSSION

This experiment is important, because, as far as we know, no one in history (including adults) has done this experiment before. It tells us that bees can learn to solve puzzles (and if we are lucky we will be able to get them to do Sudoku in a couple of years' time). In this experiment, we trained bees to solve a particular puzzle. The puzzle was go to blue if surrounded by yellow, but yellow if surrounded by blue.

Test 1 showed that the bees learned to solve this puzzle. We know this because the test results showed that they mostly went to the flowers that they were supposed to go to, because those were the ones that had contained a sugar reward before. However, we also noticed that the bees solved the puzzle in different ways, and that some were more clever than others. Two bees preferred yellow and two others preferred blue flowers. The B bee was best at understanding the pattern in the first test, because it had the most correct answers compared to incorrect answers. It also went both to correct yellow and correct blue flowers, although it preferred the blue flowers.

What is important about this puzzle is that there is more than one strategy the bees could use to solve it. One strategy would be to use two rules: (i) go to the middle four flowers in each panel, and (ii) ignore the colour. Another strategy would be to go to yellow if surrounded by blue or blue if surrounded by yellow. They could also learn to *avoid* the surrounding flowers, and as a result only go to the middle flowers. Or they could go to the fewest number of coloured flowers in each panel. Of course they could also have chosen randomly, and they might get them right or they might get them wrong. Or they could have just gone to a colour, but then they would not have solved the whole puzzle, only half of it.

Test 2 tested whether the bees had learned to go to the middle of each panel and ignored the colour. If this was true then they should have gone to the green flowers. If they had learned to go to only middle blue and yellow flowers, then they should have gone either to the surrounding blue and yellow flowers or no flowers at all. The results tell us that three of the bees preferred to go to the colours that they had learned before, and avoided the middle green flowers. Two of the bees, however, mainly went to the middle flowers, including the B bee, which went to both correct yellow and correct blue flowers during the first (control) test. So they had learned to solve the puzzle using different rules. Test 3 also showed that one of the rules was not just to go to any middle flower, as they rarely went to the middle flowers, or to go to the flowers that had the fewest colours in each panel, because they did not prefer the corner flowers. Instead, they seemed to select the flowers at random, but funnily continued to go to their 'favourite' colour.

We conclude that bees can solve puzzles by learning complex rules, but sometimes they make mistakes. They can also work together (indirectly) to solve a puzzle. Which means that bees have personality and have their personal 'likings'. We also learned that the bees could use the 'shape' of the different patterns of individual flowers to decide which flowers to go to. So they are quite clever, because they can memorize a pattern. This might help them get more pollen from flowers by learning which flowers might be best for them without wasting energy. In real life this might mean that they collect information and remember that information when going into different fields. So if some plants die out, they can learn to find nectar in another type of flower.

Before doing these experiments we did not really think a lot about bees and how they are as smart as us. We also did not think about the fact that without bees we would not survive, because bees keep the flowers going. So it is important to understand bees. We discovered how fun it was to train bees. This is also cool because you do not get to train bees everyday. We like bees. Science is cool and fun because you get to do stuff that no one has ever done before. (Bees—seem to—think!)

We thank the whole of the Blackawton community, who truly engaged with the science research, including the George Inn—where the manuscript was written—for the free Cokes for the children (and pints for others). We thank the local parish for the use of the Norman church, where the experiments were run, and the parents for letting their children 'work' outside 'normal' school hours. Of course none of this would have happened without the innovative and enthusiastic support of the teachers of Blackawton. We are also indebted to Larry Maloney and Natalie Hempel de Ibarra for their openness to possibility and time, effort and detail in writing the commentary, as well as Dale Purves, Lars Chittka, Read Montague, Karl Friston and Geoff North (*Current Biology*) for their sage advice. Finally, we thank Chris Frith and Brian Charlesworth for their openmindedness. The project was funded privately by Lottolab Studio, as the referees argued that young people cannot do real science.