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## Animal behaviour

# Label-based expectations affect incentive contrast effects in bumblebees

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While classic models of animal decision-making assume that individuals assess the absolute value of options, decades of research have shown that rewards are often evaluated relative to recent experience, creating incentive contrast effects. Contrast effects are often assumed to be purely sensory, yet consumer and experimental psychology tell us that label-based expectations can affect value perception in humans and rodents. However, this has rarely been tested in non-model systems. Bumblebees forage on a variety of flowers that vary in their signals and rewards and show contrast when rewards are lowered. We manipulated bees' expectations of stimulus quality, before downshifting the reward to induce incentive contrast. We found that contrast effects were not solely driven by experience with a better reward, but also influenced by experience with associated stimuli. While bees' initial response did not differ between treatments, individuals were faster to accept the lower-quality reward when it was paired with a novel stimulus. We explored the boundaries of these label-based expectations by testing bees along a stimulus gradient and found that expectations generalized to similar stimuli. Such reference-dependent evaluations may play an important role in bees' foraging choices, with the potential to impact floral evolution and plant community dynamics.

## 1. Introduction

Classic foraging theory assumes that animals know or can easily assess the absolute value of different options [1,2]. However, a wealth of studies in humans and other animals have demonstrated that rewards are often not perceived in absolute terms. Rather, choices are compared to other options available or to reference points (e.g. [3–5]). This idea forms the basis of Prospect Theory in behavioural economics, which suggests that decision-making is based on the perception of gains and losses relative to a reference point [6,7]. Reference-based evaluation has the potential to create incentive contrast effects, where a discrepancy between reward expectations and perceived value can lead to an exaggerated response of aversion or preference. A consequence of this is that identical options can be perceived differently depending on an individual's recent experience. Incentive contrast effects are taxonomically broad, having been demonstrated across animals such as mice [8], dogs [9], starlings [10] and goldfish [11].

Humans' expectations of reward quality are often based on experience with associated stimuli (e.g. product labels), which can serve as strong reference points in value perception [12–14]. These label-based expectations can influence decisions in several ways. Product labels similar to those of previously encountered products can lead consumers to accept rewards that would otherwise be less preferred or even rejected, a process known as 'assimilation' [15]. Conversely, labels can also have the opposite effect: if an individual expects a higher-quality reward based on a familiar label and then encounters a lower-quality one, this can lead to increased aversion [16]. For instance, people given cheap wine from a fancy bottle might enjoy the wine more than if it were poured from its

original bottle or they may show stronger aversion than those who are given the cheap wine in its original bottle [17].

Reference-based evaluation may be particularly relevant to animals with broad diets, allowing individuals to link sensory properties of foods to their nutritional quality [18–20]. For example, honeybees *Apis* and bumblebees *Bombus* are generalist foragers that associate floral traits such as scents, colours or patterns (i.e. akin to ‘labels’) with properties of their rewards [21–24], such as the concentration of nectar [25,26]. Bees evaluate nectar (sucrose solution) in reference to their prior experience and exhibit negative incentive contrast to a solution they previously accepted after experiencing higher-quality (i.e. concentration) sucrose [25,27–31]. Incentive contrast in bees can be explained at a sensory level (i.e. gustatory sensitivity), where the ingestion of higher-concentration sucrose reduces the apparent sweetness of lower concentration sucrose [25,28]. However, the direction and magnitude of contrast effects could also be influenced by prior experience with associated stimuli (labels) (e.g. see [27,32,33]).

In the present study we tested how bees’ label-based expectations of a floral signal (colour) influenced perception and acceptance of a lower-quality reward. In our first experiment, bees were trained to associate a colour with a high-quality sucrose reward. We then offered individuals a downshifted reward paired with either the previously trained colour or a novel colour and measured their probability of acceptance over successive visits. We both addressed bees’ first encounter with the downshifted reward, as well as how many visits it took them to accept the new reward after gaining experience with it. If bees’ response to a reduction in quality is purely sensory (i.e. governed by reward value alone), then we would expect individuals to respond similarly to the lower-quality reward, irrespective of flower colour. Conversely, if bees form specific expectations about reward quality based on associated stimuli (labels), then we would expect their responses to the downshifted reward to be dependent on whether it was paired with the familiar or novel stimulus. We found that bees took longer to accept a downshifted reward on a familiar stimulus, indicating a potential cost to flowers that appear similar but offer lower rewards. In a second experiment, we explored how similar floral stimuli needed to be to bear this cost of higher expectations.

## 2. Methods

### (a) Experiment 1: is incentive contrast affected by label-based expectations?

We used worker bumblebees *Bombus impatiens* from commercially reared colonies ( $n = 3$ ) (Koppert, USA). We used 20 bees per treatment (10 for each colour combination), with treatments equally represented across colonies (electronic supplementary material, table S2). Individuals were trained to a colour (blue or yellow) paired with a high-quality reward (8  $\mu$ l of 50% w/w sucrose) over three consecutive trials spaced 5 min apart. Within each trial, individuals visited approximately 10 rewarding flowers and consumed all rewards (approx. 10 min per trial); the number of flowers visited did not differ across treatments (for additional information see electronic supplementary material). Immediately following these three training trials, bees were presented with a lower-quality reward in a ‘test’ trial (8  $\mu$ l of 30% w/w sucrose) paired with either the familiar or a novel colour (figure 1a). Our experimental nectar concentrations were designed

to match natural variation found in bumblebee-visited flowers [34]. In the test trial, we recorded bees’ responses to downshifted rewards over their first 20 visits to flowers. We chose 20 successive visits based on our expectation that bees would increasingly accept the downshifted reward over this timescale. Test trials took an average of 5–10 min. Acceptance was measured as bees consuming the solution, while rejection was characterized by bees probing the solution and exiting the flower without imbibing (electronic supplementary material, video S1).

### (b) Experiment 2: do responses generalize to similar stimuli?

To determine how similar stimuli needed to be to bear the cost of higher expectations, we tested bees using a range of colour stimuli. Individuals ( $n = 85$  from five colonies; electronic supplementary material, table S1) were trained to a blue stimulus paired with a high-quality reward across three training trials (figure 1b). We then presented individuals with one of five possible colours. Four of these stimuli ranged from blue to green and were increasingly different from the originally trained colour while still being discriminable to foragers [35] (chromatic contrasts calculated in the bee colour space model [36,37]; electronic supplementary material, table S1). The fifth colour was yellow, serving as a ‘novel’ stimulus as in Experiment 1. We used a slightly different blue stimulus in Experiment 2 than Experiment 1, while the yellow was the same across both experiments. Again, we measured individuals’ acceptance of the downshifted reward over their first 20 visits.

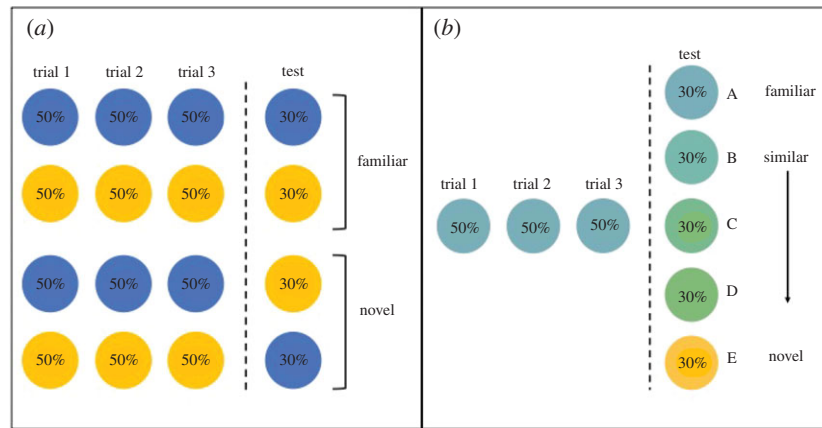
### (c) Data analysis

Analyses were carried out in R v. 4.0.5 [38]. We used generalized linear models (GLMs) and linear mixed-effect models (GLMMs) with the `glm()` and `glmer()` functions in the `lme4` package [39]. We first addressed whether bees across treatments differed from each other in their initial acceptance of the downshifted reward on their first floral visit using binomial GLMs including ‘acceptance’ (accept/reject) as the response variable and ‘stimulus type’ (familiar/novel) as the explanatory variable. After finding that treatments did not differ in their initial acceptance, to address the possibility that this was due to a lack of statistical power, we also addressed whether bees’ acceptance behaviour differed across treatments over their first five visits using binomial GLMMs including the response variable ‘acceptance’ and the explanatory variables ‘stimulus type’ (different for each experiment; see figure 1) and ‘visit number’ (continuous variable), and ‘bee’ and ‘colony’ as random factors. To determine whether bees’ acceptance behaviour varied across all 20 visits as they gained experience with the new flower type, we ran binomial GLMMs with the response variable ‘acceptance’, the explanatory variables ‘stimulus type’ (different for each experiment; figure 1), ‘visit number’ (continuous variable) and ‘bee’ as a random factor. We also included ‘colony’ as a random factor in Experiment 2, but not Experiment 1 due to a singularity issue. Finally, to determine whether the number of visits before acceptance differed across treatments, we carried out a GLM with a quasi-Poisson distribution using ‘number of visits until acceptance’ as the response variable and ‘stimulus type’ as the explanatory variable. Data and analyses are published in Dryad Digital Repository [40].

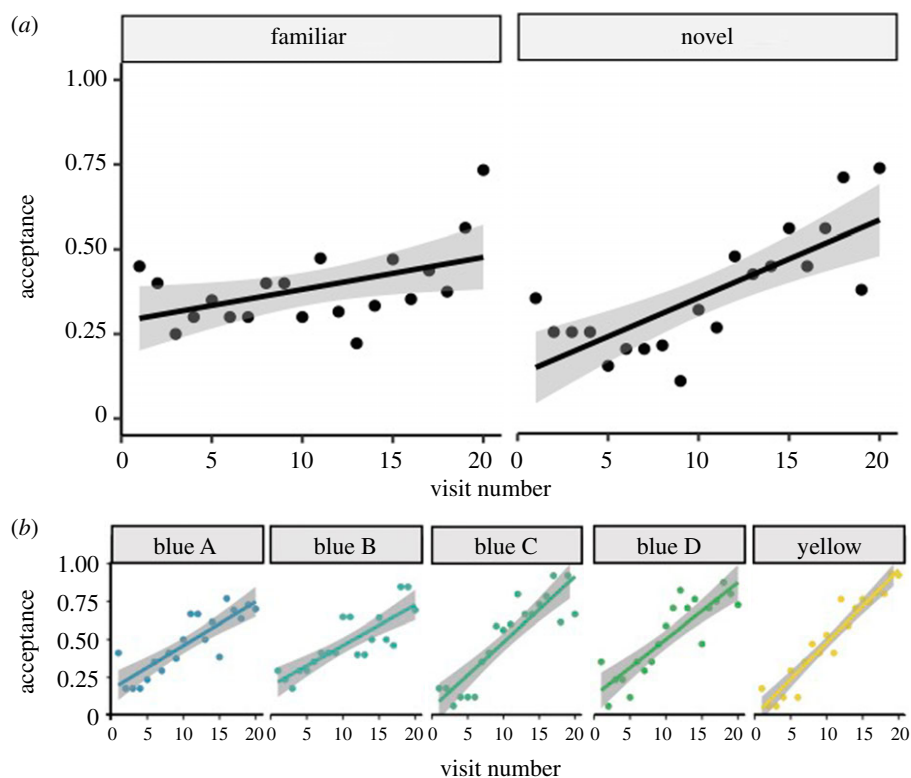
## 3. Results

### (a) Experiment 1

There was no difference between treatments in bees’ acceptance on their first visit ( $z = -0.644$ ,  $p = 0.519$ ; electronic



**Figure 1.** Experimental design for (a) Experiment 1 and (b) Experiment 2. In both experiments, we trained bees to a high-quality reward before offering them a downshifted reward paired with either a familiar, similar, or novel stimulus.



**Figure 2.** (a) Experiment 1: proportion of bees accepting downshifted rewards paired with a familiar or novel colour stimulus across the first 20 visits in the test trial. (b) Experiment 2: proportion of bees accepting the downshifted reward across visits in the test trial for all five stimuli. Shaded error bars show 95% confidence intervals.

supplementary material, figure S2), nor in acceptance across the first five visits (treatment:  $z = -1.035$ ,  $p = 0.301$ ). However, bees that encountered the novel stimulus accepted the reward faster over the first 20 visits compared with bees that encountered the same stimulus (stimulus  $\times$  visit number:  $z = 2.508$ ,  $p = 0.0122$ ; stimulus:  $z = -0.211$ ,  $p = 0.833$ ; figure 2a). As was expected from previous work on contrast effects, all bees were more likely to accept the downshifted reward over successive visits (visit number:  $z = 7.448$ ,  $p < 0.001$ ). The colour bees were trained to (blue versus yellow) did not affect acceptance (electronic supplementary material, figure S3). There was no difference between treatments in the number of visits before acceptance ( $t_{38} = 0.790$ ,  $p = 0.435$ ; electronic supplementary material, figure S4).

### (b) Experiment 2

When we tested bees across a range of stimuli that varied in their degree of difference from the trained stimulus, we found that they generalized their responses, showing similar rejection behaviour across the full range of blue/green stimuli (treatment:  $z = -1.296$ ,  $p = 0.194$ ; treatment  $\times$  visit number:  $z = 1.611$ ,  $p = 0.12$ ; figure 2b; electronic supplementary material, table S3). In line with our results from Experiment 1, we found a strong trend towards bees being more likely to accept the novel yellow colour compared to blue A across visits (yellow-blue A comparison: treatment  $\times$  visit number:  $z = 1.815$ ,  $p = 0.0696$ ; figure 2b); this effect may not have been as strong as in Experiment 1 because the stimuli were

more similar to each other (electronic supplementary material, table S1). Again, bees were more likely to accept the downshifted reward across visits ( $z = 6.268, p < 0.001$ ) and treatments did not differ in bees' acceptance on their first visit ( $z = -1.185, p = 0.236$ ; electronic supplementary material, figure S5), nor in their acceptance across the first five visits (treatment:  $z = -0.917, p = 0.359$ ). There was also no difference in the number of visits before acceptance ( $t_{83} = 0.152, p = 0.879$ ; electronic supplementary material, figure S6).

## 4. Discussion

Bees' perception of floral rewards is strongly influenced by prior experience. By comparing bees' acceptance behaviour toward downshifted rewards paired with familiar or novel colour stimuli, we found that incentive contrast effects were not only sensory but also affected by individuals' prior experience with associated stimuli. Bees' initial rejection behaviour did not differ between treatments, with individuals showing high rates of initial rejection in both familiar and novel treatments. Over repeated presentations, however, individuals were faster to accept a lower-quality reward when it was paired with a novel stimulus. Thus, both immediate taste perception and prior expectations based on stimulus value influence incentive contrast. While previous work has shown that bumblebees that encounter a downshifted reward are more likely to switch to a new colour than bees that encounter the same quality reward [29,30], ours is the first to demonstrate that incentive contrast effects are stimulus-dependent. These results indicate that when foraging, bumblebees will likely have different criteria of a flower's acceptability based on their previous experience with similar flower types, rather than based on their experience with floral rewards *per se*.

At a cognitive level, our results can be explained by when bees learn, they form associations between a specific stimulus and reward. If this stimulus is then changed to predict a lower-quality reward, there is a greater discrepancy between expectation and outcome than for a novel stimulus that does not carry this reward expectation. Thus, the behavioural response of rejection is stronger for the learned stimulus than the novel one. Upon repeated visits to the test flowers, bees in the familiar treatment undergo extinction of the previously learned association. While bees in the novel treatment also have expectations of reward value based on their training experience, the association will be weaker and thus they more readily accept the new flower faster. Stimulus-dependent extinction has similarly been shown to influence acceptance behaviour in honeybees [41]. Our result and proposed cognitive mechanism is supported by classic work on incentive contrast in rats [42,43]. For example, rats only showed incentive contrast in contexts when they expected a higher reward, and not in contexts that predicted a lower reward [43]. However, while this topic has been explored in experimental psychology using model organisms, few studies have directly addressed how label-based expectations influence acceptance behaviour in other animals and in ecologically relevant scenarios. One exception comes from a study using ants (*Lasius niger*) that found equivalent results to our own [33]. However, in a different study with this species, when the odour of the reward was manipulated, ants formed label-based expectations in the opposite direction (assimilation), consuming more of the downshifted reward when it contained the odour that was

previously associated with a high-quality reward [32]. This result may be explained by the odour cues being incorporated into the reward itself rather than the label or associated stimulus, meaning that the odour-containing downshifted reward may have been perceived as more similar to the previous, higher-quality reward instead of altering ants' reward expectation.

What are the implications of our findings for bumblebee foraging behaviour? Floral rewards can be dynamic, with nectar concentration varying within and between species [44–46]. Bumblebees can respond flexibly to this variability, switching between the flowers they visit based on their reward history [47,48]. When a flower type or patch drops in reward value, foragers will switch to visiting alternative food sources. For instance, bumblebees will fly farther and bypass more flowers following a sequence of encounters with unrewarded flowers [49]. Results from the present study suggest that, in addition to this, bees may have different acceptability thresholds of different flowers depending on their previous experience with the same or similar species.

In our second experiment, we found that bees generalized their expectations of quality to similar colours; this finding is in line with our understanding of how bees learn, requiring differential conditioning for fine-colour discrimination such as this [50,51] (as opposed to absolute conditioning used in these experiments). These results may have implications for floral signalling. Co-flowering species with similar floral traits (e.g. colour) can benefit from facilitation, i.e. increased fitness due to increased pollinator sharing (e.g. [52–54]). Our results indicate that there may also be costs to having similar floral traits to other species: without having similarly high rewards, these plants may bear the cost of bees being more sensitive to a lower-quality reward than they would on a novel flower. Likewise, there may be a benefit to being dissimilar: rare flower types that have a novel signal may 'get away' with offering cheaper rewards. Our findings also indicate that bees may be less tolerant of reward variability within than between species. This would both favour novel species within a patch and could exert pressure on a given species to not exceed certain limits of reward variability. Indeed, nectar sugar concentrations are generally less variable within than between species [55]. Bees' discrimination against lower-quality flowers that they expect to have higher rewards may also help explain 'honest' signalling of floral rewards within [56] and across species [57].

Taken as a whole, our results indicate that floral signals can serve as labels that mediate bees' expectations of floral rewards. Of course, real flowers have additional levels of complexity such as multimodal stimuli [58] and multiple rewards [59–61]. Future work might address how bees' relative value perception of flowers is affected by multiple rewards on different axes of reward quality [62]. Additionally, real flowers will have greater variability in reward quality than the artificial flowers used here, and this variability may differ across floral communities [44,63]. Going forward, future research could explore how this environmental noise influences incentive contrast effects. By determining how decision-making is guided by experience with floral stimuli, we can make more informed predictions both about bees' foraging behaviour and the evolution of signalling traits in flowers.

**Ethics.** In the United States, bees are not covered under the Institutional Animal Care and Use Committee and do not require any

permitting for experimental study. All care was taken while training and testing animals. Bees were euthanized via freezing following experiments.

**Data accessibility.** Data and code are published in Dryad Digital Repository: <https://doi.org/10.5061/dryad.08kpr543> [40].

**Authors' contributions.** C.T.H.: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, visualization, writing—original draft, writing—review and editing; F.M.: conceptualization, formal analysis, funding acquisition, investigation,

methodology, project administration, resources, software, supervision, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

**Competing interests.** We declare we have no competing interests.

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## References

- Charnov EL. 1976 Optimal foraging, the marginal value theorem. *Theor. Popul. Biol.* **9**, 129–136. (doi:10.1016/0040-5809(76)90040-X)
- MacArthur RH, Pianka ER. 1966 On optimal use of a patchy environment. *Am. Nat.* **100**, 603–609. (doi:10.1086/282454)
- Freidin E, Kacelnik A. 2011 Rational choice, context dependence, and the value of information in European starlings (*Sturnus vulgaris*). *Science* **334**, 1000–1002. (doi:10.1126/science.1209626)
- Bateson M, Healy SD, Hurly TA. 2003 Context-dependent foraging decisions in rufous hummingbirds. *Proc. R. Soc. Lond. B* **270**, 1271–1276. (doi:10.1098/rspb.2003.2365)
- Lea AM, Ryan MJ. 2015 Irrationality in mate choice revealed by túngara frogs. *Science* **349**, 964–966. (doi:10.1126/science.aab2012)
- Kahneman D, Tversky A. 1979 Prospect theory: an analysis of decisions under risk. *Econometrica* **47**, 313–327. (doi:10.2307/1914185)
- Tversky A, Kahneman D. 1986 Rational choice and the framing of decisions. *J. Bus.* **59**, 251–278. (doi:10.1086/296365)
- Mustaca AE, Bentosela M, Papini MR. 2000 Consummatory successive negative contrast in mice. *Learn. Motiv.* **31**, 272–282. (doi:10.1006/lmot.2000.1055)
- Dzik V, Cavalli C, Iglesias M, Bentosela M. 2019 Do dogs experience frustration? New contributions on successive negative contrast in domestic dogs (*Canis familiaris*). *Behav. Processes* **162**, 14–19. (doi:10.1016/j.beproc.2019.01.007)
- Freidin E, Cuello MI, Kacelnik A. 2009 Successive negative contrast in a bird: starlings' behaviour after unpredictable negative changes in food quality. *Anim. Behav.* **77**, 857–865. (doi:10.1016/j.anbehav.2008.12.010)
- Couvillon PA, Bitterman ME. 1985 Effect of experience with a preferred food on consummatory responding for a less preferred food in goldfish. *Anim. Learn. Behav.* **13**, 433–438. (doi:10.3758/BF03208020)
- French A, Smith G. 2013 Measuring brand association strength: a consumer-based brand equity approach. *Eur. J. Mark.* **47**, 1356–1367. (doi:10.1108/0309056131124363)
- Lee WJ, Shimizu M, Kniffin KM, Wansink B. 2013 You taste what you see: do organic labels bias taste perceptions? *Food Qual. Prefer.* **29**, 33–39. (doi:10.1016/j.foodqual.2013.01.010)
- Jaeger SR, Worch T, Phelps T, Jin D, Cardello AV. 2021 Effects of 'craft' vs. 'traditional' labels to beer consumers with different flavor preferences: a comprehensive multi-response approach. *Food Qual. Prefer.* **87**, 104043. (doi:10.1016/j.foodqual.2020.104043)
- Sherif M, Hovland CI. 1961 *Social judgement. Assimilation and contrast effects in communication and attitude change*. New Haven, CT: Yale University Press.
- Herr P, Sherman S, Fazio R. 1983 On the consequences of priming: assimilation and contrast effects. *J. Exp. Soc. Psychol.* **19**, 323–340. (doi:10.1016/0022-1031(83)90026-4)
- Ferreira C, Lourenço-Gomes L, Pinto LMC. 2021 Region of origin and consumers' quality perception of wine: an assimilation-contrast approach. *WEP* **10**, 57–71. (doi:10.36253/wep-9418)
- Ginane C, Duncan AJ, Young SA, Elston DA, Gordon IJ. 2005 Herbivore diet selection in response to simulated variation in nutrient rewards and plant secondary compounds. *Anim. Behav.* **69**, 541–550. (doi:10.1016/j.anbehav.2004.06.008)
- Yearsley JM, Villalba JJ, Gordon IJ, Kyriazakis I, Speakman JR, Tolkamp BJ, Illius AW, Duncan AJ. 2006 A theory of associating food types with their postingestive consequences. *Am. Nat.* **167**, 705–716. (doi:10.1086/502805)
- Bergvall UA, Rautio P, Luotola T, Leimar O. 2007 A test of simultaneous and successive negative contrast in fallow deer foraging behaviour. *Anim. Behav.* **74**, 395–402. (doi:10.1016/j.anbehav.2006.08.018)
- Menzel R, Müller U. 1996 Learning and memory in honeybees: from behavior to neural substrates. *Annu. Rev. Neurosci.* **19**, 379–404. (doi:10.1146/annurev.ne.19.030196.002115)
- Chittka L, Raine NE. 2006 Recognition of flowers by pollinators. *Curr. Opin Plant Biol.* **9**, 428–435. (doi:10.1016/j.pbi.2006.05.002)
- Jones PL, Agrawal AA. 2017 Learning in insect pollinators and herbivores. *Ann. Rev. Entomol.* **62**, 53–71. (doi:10.1146/annurev-ento-031616-034903)
- Muth F, Papaj DR, Leonard AS. 2016 Bees remember flowers for more than one reason: pollen mediates associative learning. *Anim. Behav.* **111**, 93–100. (doi:10.1016/j.anbehav.2015.09.029)
- Bitterman M. 1976 Incentive contrast in honey bees. *Science* **192**, 380–382. (doi:10.1126/science.1257773)
- Cnaani J, Thomson JD, Papaj DR. 2006 Flower choice and learning in foraging bumblebees: effects of variation in nectar volume and concentration. *Ethology* **112**, 278–285. (doi:10.1111/j.1439-0310.2006.01174.x)
- Couvillon PA, Bitterman ME. 1984 The overlearning-extinction effect and successive negative contrast in honeybees (*Apis mellifera*). *J. Comp. Psychol.* **98**, 100. (doi:10.1037/0735-7036.98.1.100)
- Wiegmann DD, Smith BH. 2009 Incentive relativity and the specificity of reward expectations in honey bees. *Int. J. Comp. Psychol.* **22**, 141–152.
- Wiegmann D, Wiegmann D, Waldron F. 2003 Effects of a reward downshift on the consummatory behavior and flower choices of bumblebee foragers. *Physiol. Behav.* **79**, 561–566. (doi:10.1016/S0031-9384(03)00122-7)
- Waldron FA, Wiegmann DD, Wiegmann DA. 2005 Negative incentive contrast induces economic choice behavior by bumble bees. *Int. J. Comp. Psychol.* **18**, 358–371.
- Townsend-Mehler JM, Dyer FC, Maida K. 2011 Deciding when to explore and when to persist: a comparison of honeybees and bumblebees in their response to downshifts in reward. *Behav. Ecol. Sociobiol.* **65**, 305–312. (doi:10.1007/s00265-010-1047-4)
- Wendt S, Czaczkas TJ. 2020 Labeling effect in insects: cue associations influence perceived food value in ants (*Lasius niger*). *J. Comp. Psychol.* **134**, 280–292. (doi:10.1037/com0000212)
- Wendt S, Strunk KS, Heinze J, Roeder A, Czaczkas TJ. 2019 Positive and negative incentive contrasts lead to relative value perception in ants. *eLife* **8**, e45450. (doi:10.7554/eLife.45450)
- Willmer P. 2011 Rewards 2: The biology of nectar. In *Pollination and floral ecology*. Princeton, NJ: Princeton University Press.
- Leonard AS, Dornhaus A, Papaj DR. 2011 Flowers help bees cope with uncertainty: signal detection and the function of floral complexity. *J. Exp. Biol.* **214**, 113–121. (doi:10.1242/jeb.047407)
- Skorupski P, Chittka L. 2010 Photoreceptor spectral sensitivity in the bumblebee, *Bombus impatiens* (Hymenoptera: Apidae). *PLoS ONE* **5**, e12049. (doi:10.1371/journal.pone.0012049)
- Chittka L. 1992 The colour hexagon: a chromaticity diagram based on photoreceptor excitations as a generalized representation of colour opponency. *J. Comp. Physiol. A* **170**, 533–543. (doi:10.1007/BF00199331)

38. R Core Team. 2020 *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. See <https://www.R-project.org/>.
39. Bates D, Mächler M, Bolker B, Walker S. 2015 Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **67**, 1–48. (doi:10.18637/jss.v067.i01)
40. Hemingway C, Muth F. 2021 Data and R code from: 'Label-based expectations affect reward perception in bumblebees'. Dryad Digital Repository. (doi:10.5061/dryad.08kpr543)
41. Gil M, De Marco RJ, Menzel R. 2007 Learning reward expectations in honeybees. *Learn. Mem.* **14**, 491–496. (doi:10.1101/lm.618907)
42. Shanab ME, Domino J, Steinhauer G. 1982 Sustained negative contrast obtained following signaled shifts in sucrose reinforcement. *Bull. Psychon. Soc.* **19**, 237–240. (doi:10.3758/BF03330244)
43. Daniel AM, Wood M, Pellegrini S, Norris JN, Papini MR. 2008 Can contextual cues control consummatory successive negative contrast? *Learn. Motiv.* **39**, 146–162. (doi:10.1016/j.lmot.2007.11.001)
44. Heinrich B. 1979 Resource heterogeneity and patterns of movements in foraging bumble bees. *Oecologia* **40**, 235–245. (doi:10.1007/BF00345321)
45. Pleasants J, Zimmerman M. 1983 The distribution of standing crop nectar: what does it really tell us? *Oecologia* **57**, 412–414. (doi:10.1007/BF00377188)
46. Real LA, Rathcke B. 1988 Patterns of individual variability in floral resources. *Ecology* **69**, 728–735. (doi:10.2307/1941021)
47. Dunlap AS, Papaj DR, Dornhaus A. 2017 Sampling and tracking a changing environment: persistence and reward in the foraging decisions of bumblebees. *Interface Focus* **7**, 20160149. (doi:10.1098/rsfs.2016.0149)
48. Dunlap AS, Nielsen M, Dornhaus A, Papaj DR. 2016 Foraging bumble bees weigh the reliability of personal and social information. *Curr. Biol.* **26**, 1195–1199. (doi:10.1016/j.cub.2016.03.009)
49. Dukas R, Real LA. 1993 Effects of recent experience on foraging decisions by bumble bees. *Oecologia* **94**, 244–246. (doi:10.1007/BF00341323)
50. Dyer AG, Chittka L. 2004 Fine colour discrimination requires differential conditioning in bumblebees. *Naturwissenschaften* **91**, 224–227. (doi:10.1007/s00114-004-0508-x)
51. Amaya-Márquez M, Hill P, Abramson C, Wells H. 2014 Honey bee location- and time-linked memory use in novel foraging situations: floral color dependency. *Insects* **5**, 243–269. (doi:10.3390/insects5010243)
52. Bergamo PJ, Streher NS, Wolowski M, Sazima M. 2020 Pollinator-mediated facilitation is associated with floral abundance, trait similarity and enhanced community-level fitness. *J. Ecol.* **108**, 1334–1346. (doi:10.1111/1365-2745.13348)
53. Coetzee A, Seymour CL, Spottiswoode CN. 2021 Facilitation and competition shape a geographical mosaic of flower colour polymorphisms. *Funct. Ecol.* **35**, 1914–1924. (doi:10.1111/1365-2435.13851)
54. Peter CI, Johnson SD. 2008 Mimics and magnets: the importance and ecological facilitation in floral deception. *Ecology* **89**, 1583–1595. (doi:10.1890/07-1098.1)
55. Nicolson S, Thornburg R. 2007 Nectar chemistry. In *Nectaries and nectar*, pp. 215–264. Berlin, Germany: Springer.
56. Nuttman C, Willmer P. 2003 How does insect visitation trigger floral colour change?: *Bombus terrestris* and floral colour change. *Ecol. Entomol.* **28**, 467–474. (doi:10.1046/j.1365-2311.2003.00527.x)
57. Ortiz PL, Fernández-Díaz P, Pareja D, Escudero M, Arista M. 2021 Do visual traits honestly signal floral rewards at community level? *Funct. Ecol.* **35**, 369–383. (doi:10.1111/1365-2435.13709)
58. Leonard AS, Masek P. 2014 Multisensory integration of colors and scents: insights from bees and flowers. *J. Comp. Physiol. A* **200**, 463–474. (doi:10.1007/s00359-014-0904-4)
59. Simpson BB, Neff JL. 1981 Floral rewards: alternatives to pollen and nectar. *Ann. Mo. Bot. Gard.* **68**, 301. (doi:10.2307/2398800)
60. Muth F, Papaj DR, Leonard AS. 2015 Colour learning when foraging for nectar and pollen: bees learn two colours at once. *Biol. Lett.* **11**, 20150628. (doi:10.1098/rsbl.2015.0628)
61. Muth F, Papaj DR, Leonard AS. 2017 Multiple rewards have asymmetric effects on learning in bumblebees. *Anim. Behav.* **126**, 123–133. (doi:10.1016/j.anbehav.2017.01.010)
62. Francis JS, Acevedo CR, Muth F, Leonard AS. 2019 Nectar quality changes the ecological costs of chemically defended pollen. *Curr. Biol.* **29**, R679–R680. (doi:10.1016/j.cub.2019.05.046)
63. Parachnowitsch AL, Manson JS, Sletvold N. 2019 Evolutionary ecology of nectar. *Ann. Bot.* **123**, 247–261. (doi:10.1093/aob/mcy132)