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Visual Biomimetics and Foraging Status Shape Honeybee Responses to Robotic Agents

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ABSTRACT

Animal–Robot Interaction (ARI) provides a controlled framework for investigating animal behavior and developing socially interactive robots. A key challenge is determining which biologically inspired features enable artificial agents to influence animal decisions and how such effects depend on behavioral state. Here, these questions are investigated in the Italian honeybee (*Apis mellifera ligustica*). An ARI platform was developed including robotic agents with three levels of visual biomimetic realism: full biomimetic agents (FBAs), partial biomimetic agents (PBAs), and Nonbiomimetic agents (NBAs). Their ability to induce local enhancement, defined as increased selection of an associated food source, was tested in two-choice assays with newly emerged, foraging-naïve workers and experienced foragers. Food-source selection, choice latency, and time to feeding were quantified, with confined living honeybees serving as a biological reference. Experienced foragers preferentially selected food sources associated with FBAs and living honeybees, whereas PBAs and NBAs did not induce significant preferences. Newly emerged workers showed no significant preference for any agent category or living honeybees, although agent configuration influenced temporal aspects of behavior. These findings demonstrate that responses to visual robotic agents depend on foraging status and highlight the importance of behavioral maturation and sensory context when designing socially interactive and adaptive robots.

1 | Introduction

How animals recognize, interpret, and exploit socially relevant information is a fundamental question in behavioral biology and an increasingly important challenge for bio-inspired robotics. In natural environments, foraging decisions can integrate individually acquired experience with information generated by other animals, potentially reducing exploration costs while improving resource exploitation [1, 2]. Understanding which social cues influence decisions, and how their effectiveness varies with the recipient's state is also relevant to adaptive robotic systems. Such systems may monitor an interaction partner's response and adjust the type, intensity, or combination of cues they provide, supporting context-sensitive robot–animal interactions and decentralized control strategies.

Among social insects, the honeybee (*Apis mellifera* Linnaeus, 1758) is a major model of socially mediated decision-making because colony foraging depends on the acquisition, transmission, and integration of information among nestmates [3, 4]. Beyond long-distance recruitment by the waggle dance [5], honeybee foragers can use inadvertent social information available directly at food sources. In *A. mellifera*, the presence and number of conspecific foragers on flowers influence landing decisions, with more highly occupied flowers receiving more landings [6]. This response is consistent with local enhancement, defined here as an increased probability of approaching or selecting a location because another individual is present there. However, responses to occupied flowers are context-dependent and may also be affected by competition, resource depletion, and scent marking [7].

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Comparative studies show that other bee taxa also use visually available social information. Bumblebees respond to bee-shaped models with conspecific-like coloration [8] and preferentially use bee-like clay models when variable rewards increase the expected value of social information [9]. A mobile model demonstrator can also facilitate acquisition of a novel object-manipulation task in bumblebees [10], complementing broader syntheses of social learning in insects [11]. Stingless bees similarly use nestmate and heterospecific occupancy at food sources [12]. These studies provide comparative support for the importance of local social cues but should not be treated as direct evidence for honeybees.

The use of local social information may vary with age, behavioral maturation, task specialization, motivation, and associative experience. Newly emerged honeybee workers normally perform in-hive tasks and have not yet developed the full behavioral repertoire of foragers. Experienced foragers, by contrast, may have learned associations between conspecific presence and profitable resources [13]. The comparison of these groups therefore addresses differences in foraging status, but cannot isolate learning from the endogenous and motivational changes associated with worker ontogeny.

ARI provides standardized artificial partners through which selected stimulus components can be manipulated [14–16]. Socially interactive systems range from agents delivering predefined stimuli to closed-loop platforms that modify their output in response to animal behavior. Depending on the question, they may reproduce selected visual, chemical, acoustic, thermal, tactile, or movement-related features rather than the complete phenotype of the model organism [17, 18]. Honeybee robots have reproduced components of dance communication and modulated collective organization through local stimuli [19–22], while magnetically actuated agents have induced local enhancement in another foraging insect [23].

Greater biomimetic similarity is often expected to facilitate behavioral acceptance, but overall resemblance alone does not determine an artificial agent's effectiveness. Responses depend on whether the agent reproduces features, or combinations of features, that the animal can perceive and use as relevant cues [17]. Here, I compared predefined visual configurations resembling *A mellifera*: full biomimetic agents (FBAs), partial biomimetic agents (PBAs), nonbiomimetic agents (NBAs), and confined living honeybees. I tested whether these configurations influenced food-source selection and response timing in newly emerged, foraging-naïve workers and experienced foragers. The labels full, partial, and nonbiomimetic refer only to the implemented visual design space. Full does not imply complete multimodal equivalence to a living honeybee.

2 | Materials and Methods

2.1 | Study Species

Workers of the Italian honeybee, *Apis mellifera ligustica* Spinola, 1806, were obtained from a healthy colony maintained under standard apicultural conditions in Pisa, Italy. Two categories were tested: newly emerged, foraging-naïve workers, and experienced foragers. Following the general procedure used to obtain newly emerged workers from brood frames [24], individuals that had emerged within the preceding 24 h were collected directly from brood frames. They were operationally classified as foraging-naïve because workers of this age do not normally leave the hive to forage. This classification does not imply absence of all prior sensory or social experience. Experienced foragers were captured individually at the hive entrance during peak foraging hours while returning to the colony and were identified by visible pollen loads on their hind legs. They were not individually marked; therefore, no inference was made about the number of previous foraging trips. Capture upon return may also have involved an immediate motivational state oriented towards unloading. Each focal bee was isolated in an individual container, tested once, and never reused.

All experimental procedures complied with ethical standards for animal research [25] and with relevant Italian (D.M. 116192) and European regulations [26]. Experiments involved only noninvasive behavioral observations.

2.2 | Artificial Agents

Artificial agents were used as standardized conspecific-like stimuli within the ARI framework. All agents were fabricated by additive manufacturing using biocompatible transparent resin (VisiJet M3 Crystal, 3D Systems).

Three categories of agents were used (Figure 1):

(i) FBAs, which reproduced the complete set of visual features implemented in this study: overall honeybee-like morphology, size, naturalistic coloration, and surface patterning, including distinct head, thorax, abdomen, wings, legs, and antennae.

(ii) PBAs, which retained the same honeybee-like morphology and dimensions as FBAs but lacked naturalistic coloration and surface patterning and were uniformly white.

(iii) NBAs, which were uniformly white simplified elliptical objects matched approximately to honeybee body dimensions.



FIGURE 1 | Representative images of the three artificial agents used in the study. From left to right: Partial biomimetic agent (PBA), retaining honeybee morphology and size but with a white surface; full biomimetic agent (FBA), replicating honeybee morphology, size, and coloration; and nonbiomimetic agent (NBA), a white elliptical object of comparable dimensions.

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FBAs were coated with nontoxic pigments. Each agent measured approximately 20 mm in body length and 10 mm in wingspan. The three categories were predefined, hierarchically structured visual configurations rather than a factorial manipulation of individual traits. Thus, the FBA–PBA contrast primarily evaluated naturalistic coloration and surface patterning within a shared honeybee-like morphology, whereas the PBA–NBA contrast evaluated detailed morphology as a whole but did not isolate wings, legs, antennae, or other structures. A honeybee-colored NBA was not tested. The term full therefore denotes the full set of implemented visual features and not chemical, tactile, acoustic, thermal, or fully interactive behavioral equivalence.

2.3 | Robotic Actuation System and Experimental Apparatus

The robotic actuation system used the established external architecture described by Romano and Stefanini [23], modified for the present species and coupling interface. Whereas the earlier agents contained embedded iron filings, the present honeybee agents incorporated neodymium magnets coupled to external magnets beneath the arena.

Each artificial agent contained a cylindrical N35 neodymium magnet measuring 2 mm in diameter and 2 mm in thickness. The magnet was nickel-coated, axially magnetized, and had a manufacturer-reported nominal pull force of 0.12 kg. Each agent was coupled to an external magnet driven beneath the arena by one of three servomotors mounted radially on a circular polyvinyl chloride base (diameter 100 mm). Each external magnet traveled along a 180° arc with a radius of 10 mm.

The same movement program was applied to FBAs, PBAs, and NBAs. Each agent traveled outward and back along its arc at approximately 20 mm s^{-1}, a speed selected from preliminary observations of undisturbed worker honeybees walking on comb under routine colony conditions. Each complete outward-and-return cycle was followed by a 2 s stationary interval. After five cycles, the initial direction along the arc was reversed to reduce directional repetitiveness. The servomotors were controlled asynchronously by an Arduino Mega 2560 microcontroller connected to an external computer (Dell XPS, Intel Core i7), and the program remained active throughout each trial. It was intended to approximate the speed and intermittent character of routine comb locomotion, not the waggle dance or another specific communicative display.

Behavioral trials were conducted in a two-choice arena (300 mm × 300 mm) divided into three compartments: one release section and two stimulus sections (Figure 2b). The release section was connected to both stimulus sections, while the stimulus sections were separated by an opaque partition to prevent cross-visibility.

The arena was enclosed within a transparent box (300 mm × 300 mm × 100 mm) and further surrounded by an opaque Plexiglas enclosure (500 mm × 500 mm × 500 mm) to minimize external visual disturbances. The floor of the arena was lined with filter paper impregnated with beeswax. Herein, I followed the rationale adopted in previous honeybee behavioral and biohybrid robotics studies in which beeswax foundations or beeswax sheets were used as the arena floor [21, 22]. Indeed, beeswax represents the primary nesting material of honeybees and provides a biologically relevant substrate associated with the comb environment, thereby allowing the animals to be tested on the surface more closely resembling a familiar colony-related context [27]. To prepare this substrate, molten beeswax was poured onto the filter paper and allowed to permeate its fibers. After cooling, the continuous layer of wax solidified above the paper surface was carefully removed, leaving a thin and uniformly wax-impregnated sheet. Only the wax-impregnated paper, rather than the overlying solid wax layer, was retained. This minimized friction between

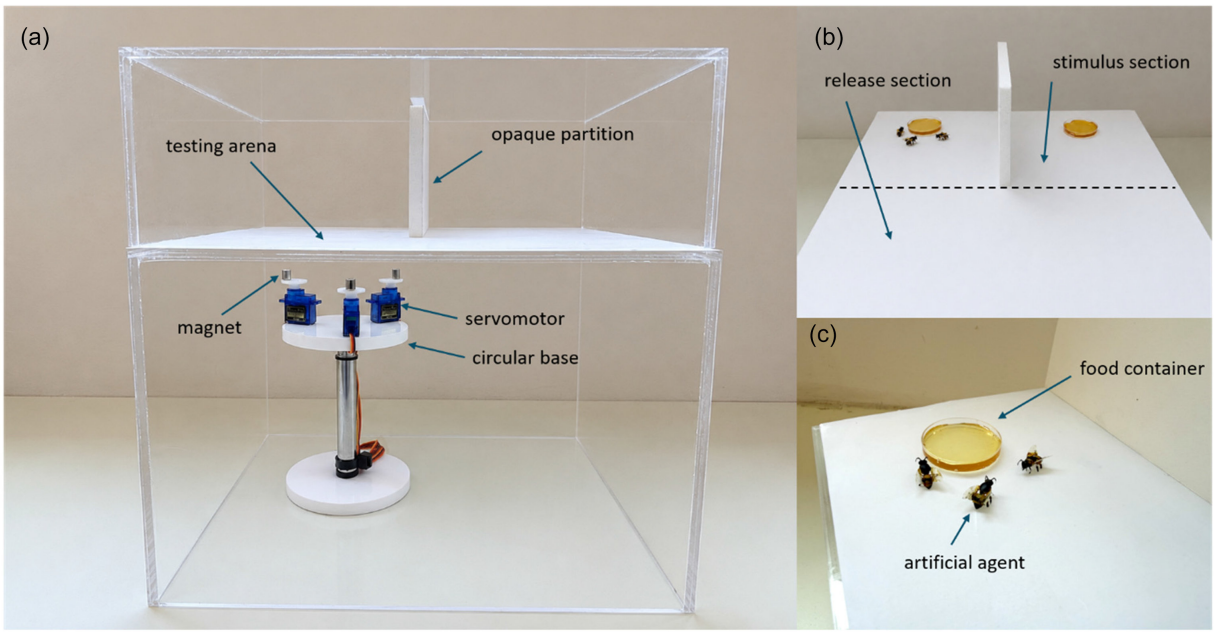


FIGURE 2 | Experimental apparatus and arena configuration. (a) General view of the experimental apparatus with the robotic actuation system located underneath the arena. (b) Overhead view of the testing arena showing the spatial arrangement of the food containers, arena sections, and artificial agents. (c) Close-up of the full biomimetic agents (FBAs) positioned around a food container in a stimulus section.

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the arena floor and the magnets driving the artificial agents and ensured smoother and more consistent agent displacement. Removal of the solid wax layer also prevented surface deformation, cracking, and bending caused by wax contraction during cooling, thereby maintaining a flat and mechanically stable experimental surface. A transparent top and lateral panel allowed focal observation.

Each stimulus section contained a central food container filled with sucrose solution. In every trial, one food source was surrounded by three stimuli of the same assigned category: three FBAs, three PBAs, three NBAs, or three individually confined living honeybees. The opposite section contained an identical food source without agents or confined bees. In the biological-reference condition, the three adult honeybees were held individually in transparent stationary cylinders. Each could move spontaneously within its cylinder but could not leave it or physically interact with the focal bee. Their movements were neither standardized nor quantitatively matched to the artificial trajectories. The side containing the stimuli and, for artificial agents, the actuation system was alternated across trials.

3 | Experimental Section

Individual bees were introduced into the arena using a cylindrical release container placed at the center of the release section. The container featured a small apical opening (diameter 10 mm), allowing the bee to exit voluntarily.

A trial began when the focal bee fully exited the release container. Choice latency was the time from this event to first entry into either stimulus section. A transient boundary crossing was insufficient to define a choice: the bee had to remain in the entered section for at least 5 s, and all individuals entering a section satisfied this criterion. If the stimulus-free section was selected, the trial ended after the 5 s criterion. If the stimulus-associated section was selected, observation continued until the bee initiated feeding by contacting the food with its mouthparts. All bees selecting the stimulus-associated section subsequently fed there. Entries, exits, and subsequent transitions between sections were not recorded as separate variables.

The experiment followed a fully between-subjects 2×4 factorial design comprising two focal-bee groups (newly emerged, foraging-naïve workers and experienced foragers) and four stimulus conditions (FBA, PBA, NBA, and living honeybees). Each group × condition combination included 50 focal individuals, giving a total sample size of 400. Each focal bee was assigned to one condition, participated in one trial, and was never reused. The living-honeybee condition was a biological reference, not an additional trial experienced by all subjects. The recorded outcomes were section choice, choice latency, and, for bees selecting the stimulus-associated section, time from release-container exit to feeding onset. The latter outcome was available for 254 bees. Switching after the initial sustained choice was not quantified.

4 | Statistical Analysis

Binary section choice was analyzed using a binomial generalized linear model with a logit link, including focal-bee group, stimulus condition, and their interaction. Within each group × condition combination, preference for the stimulus-associated versus stimulus-free section was additionally evaluated using exact two-sided binomial tests against a probability of 0.5. Holm's sequential procedure controlled family-wise error across the eight tests.

Choice latency was available for all 400 bees and was log-transformed before analysis with a linear model including focal-bee group, stimulus condition, selected section, and all interactions. Time to feeding was structurally available only for the 254 bees selecting the stimulus-associated section and was analyzed conditionally using a linear model including group, condition, and their interaction. Heteroscedasticity-consistent HC3 standard errors were used for continuous outcomes. Model-based contrasts were adjusted using Holm's procedure within each comparison family. Analyses were performed in Python 3.12.13 using pandas 2.2.3, NumPy 2.3.5, and SciPy 1.17.0. All tests were two-sided with alpha = 0.05; p values below 0.001 are reported as $p < 0.001$.

5 | Results

Binary choice varied significantly with focal-bee group (likelihood-ratio chi-square = 10.10, df = 1, $p = 0.001$) and stimulus condition (likelihood-ratio chi-square = 13.96, df = 3, $p = 0.003$), whereas the group × condition interaction was not significant (likelihood-ratio chi-square = 5.15, df = 3, $p = 0.161$).

Newly emerged, foraging-naïve workers showed no significant preference in any condition after Holm correction: 28 of 50 selected the FBA-associated section, 26 of 50 selected the PBA-associated section, 26 of 50 selected the NBA-associated section, and 32 of 50 selected the section with living honeybees (all Holm-adjusted $p > 0.05$). Experienced foragers significantly preferred the stimulus-associated section with FBAs (39 of 50, Holm-adjusted $p < 0.001$) and living honeybees (44 of 50, Holm-adjusted $p < 0.001$), but not with PBAs (32 of 50, Holm-adjusted $p = 0.389$) or NBAs (27 of 50, Holm-adjusted $p > 0.05$). Figure 3 summarizes these choices.

For log-transformed choice latency, the group × condition × selected–section interaction was significant (Wald chi-square = 20.61, df = 3, $p < 0.001$). The group × condition interaction was not significant among bees selecting the stimulus-free section (Wald chi-square = 0.60, df = 3, $p = 0.897$) but was significant among bees selecting the stimulus-associated section (Wald chi-square = 63.23, df = 3, $p < 0.001$). Experienced foragers had shorter latency than newly emerged workers in every condition and selected-section stratum (all Holm-adjusted $p < 0.001$).

Among bees selecting the stimulus-associated section, newly emerged workers reached that section more rapidly in the FBA and living-honeybee conditions than in the PBA and NBA conditions; FBA and living honeybees did not differ. PBA also produced shorter latency than NBA. Experienced foragers similarly showed shorter latency with FBA and living honeybees than with PBA or NBA; FBA and living honeybees did not differ, and PBA and NBA did not differ. No condition contrast was significant among bees selecting the stimulus-free section. Complete contrasts are reported in Table 1 and distributions in Figure 4a,b.

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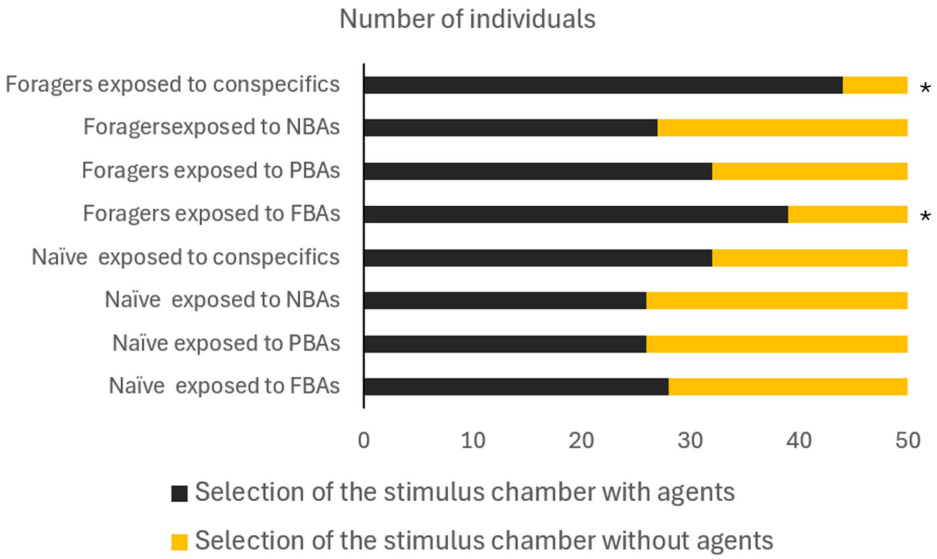


FIGURE 3 | Choices of newly emerged, foraging-naïve workers and experienced foragers in two-choice assays. Bars show the number selecting the stimulus-associated or stimulus-free food source in FBA, PBA, NBA, and living-honeybee conditions. Asterisks indicate exact two-sided binomial tests that remained significant after Holm correction across eight comparisons (adjusted $p < 0.001$).

TABLE 1 | Pairwise stimulus-condition contrasts for log-transformed choice latency, stratified by focal-bee group and selected section.

Group	Selected section	Contrast	Ratio	SE (log)	Adjusted *p*
Naïve	Stimulus-free	FBA–living	0.942	0.085	1.000
Naïve	Stimulus-free	FBA–NBA	0.921	0.087	1.000
Naïve	Stimulus-free	FBA–PBA	0.966	0.089	1.000
Naïve	Stimulus-free	NBA–living	1.023	0.070	1.000
Naïve	Stimulus-free	PBA–living	0.975	0.074	1.000
Naïve	Stimulus-free	PBA–NBA	0.953	0.075	1.000
Naïve	Stimulus-associated	FBA–living	1.001	0.046	0.974
Naïve	Stimulus-associated	FBA–NBA	0.552	0.048	<0.001
Naïve	Stimulus-associated	FBA–PBA	0.690	0.059	<0.001
Naïve	Stimulus-associated	NBA–living	1.815	0.049	<0.001
Naïve	Stimulus-associated	PBA–living	1.452	0.060	<0.001
Naïve	Stimulus-associated	PBA–NBA	0.800	0.062	<0.001
Forager	Stimulus-free	FBA–living	1.030	0.108	1.000
Forager	Stimulus-free	FBA–NBA	0.987	0.057	1.000
Forager	Stimulus-free	FBA–PBA	1.025	0.086	1.000
Forager	Stimulus-free	NBA–living	1.044	0.107	1.000
Forager	Stimulus-free	PBA–living	1.006	0.125	1.000
Forager	Stimulus-free	PBA–NBA	0.963	0.085	1.000
Forager	Stimulus-associated	FBA–living	1.227	0.096	0.068
Forager	Stimulus-associated	FBA–NBA	0.422	0.083	<0.001
Forager	Stimulus-associated	FBA–PBA	0.425	0.074	<0.001
Forager	Stimulus-associated	NBA–living	2.905	0.081	<0.001
Forager	Stimulus-associated	PBA–living	2.886	0.071	<0.001
Forager	Stimulus-associated	PBA–NBA	0.994	0.052	0.901

Note: Ratios below 1 indicate shorter latency for the first-listed condition. *p*-values are Holm-adjusted within each group × selected-section family.

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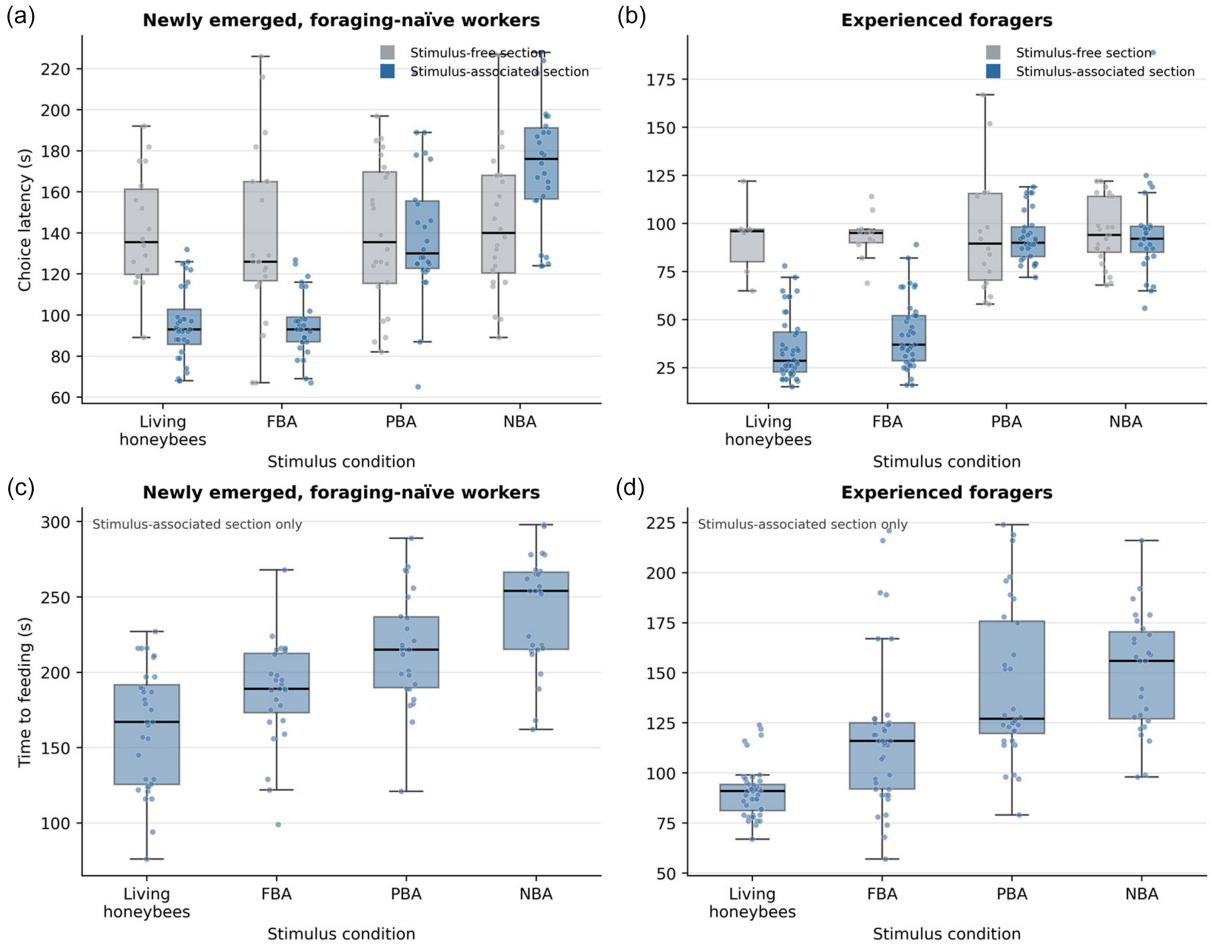


FIGURE 4 | Choice latency and time to feeding in Italian honeybees exposed to biological and artificial stimuli. (a,b) Time from release-container exit to first entry into either stimulus section for newly emerged, foraging-naïve workers (a) and experienced foragers (b), distinguished by selected section. (c,d) Time from release-container exit to feeding onset for individuals selecting the stimulus-associated section. Conditions are ordered as living honeybees, FBA, PBA, and NBA. Points represent individual observations. Boxes show medians and interquartile ranges; whiskers extend to the most extreme observation within 1.5 times the interquartile range.

Time to feeding was analyzed for the 254 bees selecting the stimulus-associated section. The group × condition interaction was not significant (Wald chi-square = 3.39, df = 3, $p = 0.335$). In the additive model, experienced foragers fed an estimated 75.02 s sooner than newly emerged workers (SE = 4.44 s; Wald chi-square = 285.68, df = 1, $p < 0.001$), and stimulus condition had a significant overall effect (Wald chi-square = 169.74, df = 3, $p < 0.001$). All six marginal condition contrasts were significant after Holm correction (Table 2; Figure 4c,d). Mean time to feeding was shortest with living honeybees, followed by FBA, PBA, and NBA in both groups.

Because time to feeding was not observed after selection of the stimulus-free section, this outcome describes post-choice progression to feeding and cannot be interpreted as an unconditional trial duration. Likewise, because transitions between sections were not recorded, the data characterize the initial sustained choice but not subsequent switching or comparative exploration.

TABLE 2 | Marginal pairwise stimulus-condition contrasts for time to feeding among bees selecting the stimulus-associated section.

Contrast	Difference, s	SE, s	Adjusted *p*
FBA–PBA	−26.79	6.74	<0.001
FBA–NBA	−42.51	6.47	<0.001
FBA–Living	26.08	5.47	<0.001
PBA–NBA	−15.73	6.93	0.023
PBA–living	52.86	6.03	<0.001
NBA–living	68.59	5.78	<0.001

Note: Negative differences indicate shorter time for the first-listed condition. *p*-values are Holm-adjusted across the six contrasts.

5.1 | Computational Perspective for Bio-Inspired Decision-Making

The present experiment was not designed to fit or validate a computational model. Each individual completed a single trial, and the study did not generate longitudinal sequences of choices and rewards from which learning parameters could be estimated. The equations below are therefore presented exclusively as a conceptual interpretation illustrating how the observed patterns might motivate computational hypotheses and bio-inspired control architectures. None of the parameters were estimated from the experimental data.

One possible computational representation would describe the perceived value of an option as the combination of personally

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acquired and socially derived information, with the latter multiplied by a state- or experience-dependent weighting term:

$$V_i = I_i + w(E)B_i$$

where V_i is the perceived value of option i, I_i represents individually acquired information about that option, B_i represents information provided by the artificial or biological stimulus associated with the option, and $w(E)$ is a hypothetical state- or experience-dependent weighting function. The behavioral differences observed here are compatible with, but do not demonstrate, differences in this weighting. Age-dependent maturation, task specialization, motivation, and associative experience remain nonmutually-exclusive explanations.

A possible decision architecture could translate option values into choice probabilities through a softmax rule:

$$P_i = \frac{e^{\beta V_i}}{\sum_j e^{\beta V_j}}$$

where P_i is the probability of selecting option i and beta would represent sensitivity to value differences. Larger beta values would produce more deterministic choices, whereas smaller values would produce more exploratory choice distributions. Beta was not estimated here, and the observed frequencies cannot establish that the groups differed in this parameter.

If implemented in a future adaptive robotic or longitudinal learning model, option values could hypothetically be updated through a reinforcement-learning rule:

$$V_i(t+1) = V_i(t) + \alpha[R_i(t) - V_i(t)]$$

where alpha would represent a hypothetical learning rate and R_i the experienced reward associated with option i. Because every bee was tested once and no repeated choice-reward sequence was recorded, the present study neither estimates alpha nor demonstrates reinforcement-based updating.

Experience-dependent weighting should therefore be treated as a testable computational hypothesis inspired by the behavioral pattern, not as an identified biological mechanism. A decentralized robotic agent could, for example, change the influence assigned to neighboring agents according to accumulated interaction history, estimated reliability, or internal state.

This perspective provides a conceptual bridge to adaptive bio-inspired robotics. Testing it would require direct implementation of fixed and adaptive weighting rules and comparison of their performance under changing environmental conditions.

6 | Discussion

Honeybee responses to artificial agents varied with both the visual configuration of the agents and the foraging status of the interacting bees. Experienced foragers preferentially selected food sources associated with FBAs and living honeybees, whereas newly emerged, foraging-naïve workers showed no significant preference. However, the group×condition interaction was not significant for binary choice or conditional time to feeding. A higher–order interaction emerged only for choice latency when the selected section was considered. The effects of agent design and focal-bee status are therefore outcome-dependent rather than evidence of a general interaction across all responses.

The absence of a population-level choice preference in newly emerged workers should not be interpreted as absence of sensitivity. Among those selecting the stimulus-associated section, latency was shorter with FBA and living honeybees than with PBA and NBA, and subsequent time to feeding also differed among configurations. Thus, agent design affected temporal components of behavior without producing a directional preference. These conditional patterns do not establish social recognition and may reflect visual salience, exploration, motivation, maturation, or other processes.

Differences between newly emerged workers and pollen-laden returning foragers cannot be assigned to associative experience alone. Honeybee workers normally progress from in-hive tasks to foraging through age-related behavioral maturation. The young workers tested here were not expected to forage, whereas returning foragers may have been motivated to unload collected resources. Learning, maturation, task specialization, and immediate motivational state are therefore nonmutually-exclusive explanations. The operational term foraging-naïve denotes absence of foraging experience, not absence of all prior social or sensory experience.

The agent labels describe predefined levels within the visual design space. Full denotes the complete set of implemented visual features, not complete biological equivalence. All artificial agents lacked chemical, tactile, acoustic, thermal, and fully interactive behavioral signals. Conclusions must therefore be restricted to the tested combinations of morphology, coloration, surface patterning, and common movement.

The greater effectiveness of FBAs is consistent with the contribution of naturalistic coloration and surface patterning, which distinguished them from morphologically equivalent PBAs. The experiment cannot determine whether responses depended on honeybee-like coloration as a meaningful pattern, on greater chromatic or achromatic contrast, or on an interaction with morphology. The FBA–NBA comparison also changes morphology and coloration simultaneously, while the absence of a honeybee-colored NBA prevents their independent separation.

The lower apparent contrast of white PBAs and NBAs against the light-colored beeswax-impregnated floor is an important limitation. The small arena limited viewing distance, and movement probably increased dynamic salience, making detection as moving objects plausible. Nevertheless, neither restricted distance nor movement demonstrates visibility equivalent to FBA or living honeybees. Reduced contrast may therefore have contributed to lower effectiveness. Movement itself was not manipulated, although previous studies show that moving artificial demonstrators or robotically actuated agents can influence insect behavior [10, 23].

Living honeybees provided multimodal signals absent from the artificial designs, although confinement also constrained their behavior and prevented physical interaction. Their spontaneous

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movement was not matched to the programed trajectories. Consequently, comparisons with this biological reference capture combined differences in visual, chemical, movement-related, and other cues rather than a single sensory dimension.

The magnetic system represents an additional limitation because honeybees can respond to magnetic anomalies [28, 29]. No equivalent actuation system was placed beneath the stimulus-free source and field intensity at the arena surface was not measured. A contribution to the overall agent-versus-no-agent comparison cannot therefore be excluded. However, side allocation was alternated and magnetic configuration was identical for FBA, PBA, and NBA, so magnetic stimulation alone cannot readily explain differences among artificial designs. An interaction with visual cues remains possible, and future studies should quantify field intensity and use magnetically matched controls.

For robotics, the findings emphasize that effectiveness is relational rather than an intrinsic property of a robot. Relevant cues must be defined from the receiver's sensory and behavioral perspective. Movement may be an additional design feature, as suggested by previous insect studies, but its independent contribution was not tested here. Likewise, adaptive weighting of social information is a candidate design principle motivated by the group differences, not a mechanism demonstrated in these bees.

A decentralized robotic system could hypothetically adjust the influence of neighboring agents according to interaction history, estimated reliability, or internal state. Direct tests should implement fixed and adaptive weighting rules and compare performance under changing conditions. This framing preserves the connection between behavioral evidence and bio-inspired control while avoiding a mechanistic inference from cross-sectional data.

Controlled artificial stimuli may eventually contribute to technologies for studying or guiding pollinator behavior. Mechanical and robotic models of the honeybee waggle dance have elicited dance-following and recruitment-related responses [20, 30]. The present experiment addresses a different scale: artificial agents located directly at a food source. Together, these approaches target distinct stages from colony-level communication to local food-site evaluation. Applications to pollination management remain prospective and require validation under naturalistic field conditions.

Future experiments should use factorial combinations of morphology and coloration, honeybee-colored simplified controls, calibrated chromatic and achromatic contrast, magnetically matched alternatives, field measurements, and direct manipulation of motion. Longitudinal designs would be required to separate learning from behavioral maturation and to estimate computational learning parameters. These extensions would identify which individual cues are necessary or sufficient and how their influence changes across behavioral development.

Despite these limitations, ARI provides a controlled framework for comparing biologically motivated stimulus configurations. The present results show that FBA and living-honeybee conditions produced similar choice-latency patterns among individuals selecting the stimulus-associated section, while only experienced foragers showed significant directional preferences for these conditions. These results provide design-relevant evidence without implying complete biomimetic equivalence or a single underlying mechanism.

Overall, visual agent configuration and foraging status shaped multiple components of honeybee behavior, but their statistical relationships differed among choice, latency, and feeding-time outcomes. The findings support careful matching of artificial cues to the sensory and behavioral context of the receiver and motivate, rather than validate, adaptive information-weighting principles for future robotic systems.

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Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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