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Behavioral Variation in Individual and Group Exploration of the Tropical Fire ant *Solenopsis geminata* (Hymenoptera: Formicidae)

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In social insects, variations in worker behavior at both individual and group levels allow for rapid responses to environmental changes. The individual and group exploration behaviors of the tropical fire ant *Solenopsis geminata* were investigated in this study. Here we examined the time individual workers spent exploring four different food items, the types of food they discovered, and the dwell time (the duration spent on each food item). We also examined whether individual variations in exploratory behavior influence group-level exploratory behavior. In the individual exploration assay, there were significant effects of nest and food on the dwell time. The average exploratory time taken by workers in the group exploration assay showed no significant difference between experienced and inexperienced workers in Nest 1. However, a significant difference was found between the groups in Nest 2. Here, observations showed that *S. geminata* workers in the group could find the food more quickly than individual workers. Our work suggested that varying degrees of exploratory behavior exist among individual workers and groups, which may potentially impact

foraging efficiency and resource utilization. The tropical fire ant, *S. geminata*, is a globally invasive species that has been introduced to Taiwan for over 40 years. Incorporating an analysis of exploratory behavior into the study of invasive species allows us to better understand the mechanisms driving their progression.

Keywords: *Solenopsis geminata*, Behavioral variation, Exploration, Individual, Group

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BACKGROUND

Social insects, such as ants, exhibit a diverse array of foraging strategies (Traniello 1989). They use available cues and various navigational strategies to locate, collect, and transport food back to their nests (Freas and Schultheiss 2018; Heyman et al. 2019). For example, the ant *Lasius niger* employs a combination of route memory and trail pheromones to optimize foraging efficiency (Czaczkes et al. 2011). Ant foragers rely not only on their own experience (personal information) but also on information received from nestmates (social information) when making foraging decisions (Kolay et al. 2020). Within a colony, variation in foraging strategies among individual workers can lead to colony-level differences in foraging behavior (Jandt and Gordon 2016).

The division of labor, where individual workers perform various tasks within the colony, is a hallmark of eusociality. Factors such as age, size, lifespan, or genotype can influence this division, creating distinct behavioral groups that carry out specific tasks (task specialization) (Hölldobler and Wilson 1990; Tripet and Nonacs 2004; Trigos-Peral et al. 2023). As far as foraging activities are concerned, individual workers may exhibit behavioral variation to perform particular tasks (Gordon 2016). In polymorphic ant species, the tasks that workers perform might be associated with their body size. For example, in *S. geminata*, large foraging workers have been observed cutting cricket prey into fragments, which are then transported back to the nest by smaller workers (Chiu et al. 2020). Furthermore, recent work suggests that labor can also be divided based on different times of the day. In leaf-cutting ants (*Atta sexdens*), larger workers participate in leaf transportation during the day, while smaller workers forage at night and are less engaged in leaf transportation (Constantino et al. 2021).

Individual behavior is regulated by the behavior of others, and collectively, it influences the group as a whole (Conradt and List 2009). In social insects, workers in colonies exhibit behavioral variation at both the individual and group levels (Jandt et al. 2014). Sih et al. (2004) described a behavioral syndrome as a set of correlated behaviors that reflect consistent individual behavior across various situations. For example, Chapman et al. (2011) noted that *Myrmica* ants exhibit behavioral syndromes and personalities at the individual, caste, and colony levels. For instance, patrollers are bolder, more aggressive, and exploratory than nurses or foragers. Additionally, in the Australian weaver ant, *Oecophylla smaragdina*, major workers tend to be more aggressive than smaller workers (Kamhi et al. 2015). In *Temnothorax longispinosus*, individual workers exhibit aggressive behavior that can influence group defensive behavior (Modlmeier et al. 2014). Thus, differences in the behavior of individual workers can affect the colony's overall tendency to explore (Pinter-Wollman 2012).

Invasive ant species have spread beyond their native ranges and are widespread (Bertelsmeier et al. 2017). Invasive ants significantly impact the ecosystems they invade as they explore new environments or search for resources. Once they successfully establish a new nest in a territory, they can expand their range and pose a threat to native species (Porter and Savignano 1990). Consequently, variations in workers' exploratory or aggressive behaviors within a colony may influence how far the nest extends its activity range (Hui and Pinter-Wollman 2014). Specifically, behavioral variation among individual workers has significant implications for collective behavior, affecting the survival and reproductive success of the colony (Hui and Pinter-Wollman 2014; Kolay et al. 2020). Additionally, it establishes the range of invasive species in the affected area and the ecological impacts they cause.

The tropical fire ant (*S. geminata*) is an invasive ant species in Taiwan, widely distributed in low-altitude areas of central, southern, and eastern Taiwan (Lai et al. 2009). In the previous study, *S. geminata* workers used random choice strategies to navigate while exploring enclosed spaces (Lai and Chao 2021), they exhibited various exploration paths in a circular arena, with most tending to search in a looping pattern that progressively increased in size (Lai et al. 2022). Individual workers of *S. geminata* exhibit variations in their exploratory patterns and durations (Lai et al. 2024). This study examines the exploratory behavior of individual workers, focusing on whether they discover food items, the types of food they find, and the duration of their stay at each food source. Investigating whether differences in individual exploratory behavior affect variations in group-level exploratory behavior. We asked whether groups composed of individuals with exploratory experience discover food more quickly than groups without such experience. We hypothesize that individual workers will spend more time searching for food than groups. Furthermore, groups consisting of individuals with exploratory experience can find food more rapidly than those without such experience. If our hypothesis is confirmed, we expect that foraging efficiency in this species will influence the entire colony and potentially impact local ant populations in the invaded ecosystem. Conversely, if our hypothesis is refuted, it would suggest that other factors, such as environmental conditions or social interactions, play a more significant role in shaping workers' exploratory behavior.

MATERIALS AND METHODS

Ant sources and maintenance

Two colonies of *S. geminata* were investigated in this study. These colonies were collected from Taichung City, Central Taiwan. Each colony (a whole nest) was excavated and maintained with soil in a plastic container (37.5 × 23.5 × 15 cm) coated with Fluon (NP115; Northern Products Inc., Woonsocket, RI, USA) to prevent the ants from escaping. Both colonies were regularly moistened and kept in the laboratory at room temperature (26–27°C), with the relative humidity ranging between 60% and 70%, and the light: dark cycle was variable. Ants were provided *ad libitum* with water, commercial insect jelly (Beetle jelly; Han Shuo Food Co., Ltd, Taiwan), and frozen crickets (*Gryllus bimaculatus*). After one week of acclimatizing to the laboratory conditions, the workers were used for behavioral experiments.

Individual Exploration Assay

In the foraging workers of *S. geminata*, two distinct groups were identified: a large worker group, constituting 25.64% of the nest (with a head width of ≥ 0.924 mm), and a small worker group, making up 74.36% of the nest (with a head width of < 0.924 mm) (Chui et al. 2020). Previous observations indicate that larger workers tend to stay hidden inside the nest during disturbances (Wilson 1978) and are primarily responsible for cutting prey, while small workers are tasked with transporting it (Chui et al. 2020). For this study, we collected small foraging workers from the nest surface to investigate their exploratory behavior in an individual exploration assay. Each foraging worker was placed at the center of a four-arm maze to observe their behavior, using a method adapted from Hui and Pinter-Wollman (2014). We aimed to control for potential behavioral differences related to worker size by selecting only small workers.

The four-arm maze utilized in this study consisted of plastic containers (6 cm diameter × 4 cm deep) with Fluon-coated walls, including a central plastic container connected to four additional plastic containers using Tygon tubes (5 cm length) (Fig. 1). We randomly placed potato chips (Original; Pringles Co., Taiwan), seeds (*Ficus subpisocarpa*), wax worms (*Galleria mellonella* larvae), and 2% honey water (BeeTouched Co., Taiwan) within these containers, allowing each worker to explore individually. Each food item weighs approximately 0.1 g. These four food items each provide different nutritional content, such as protein, lipids, and carbohydrates, for the ants to choose from. This design helps to understand how resource availability affects ants' exploration and foraging behavior.

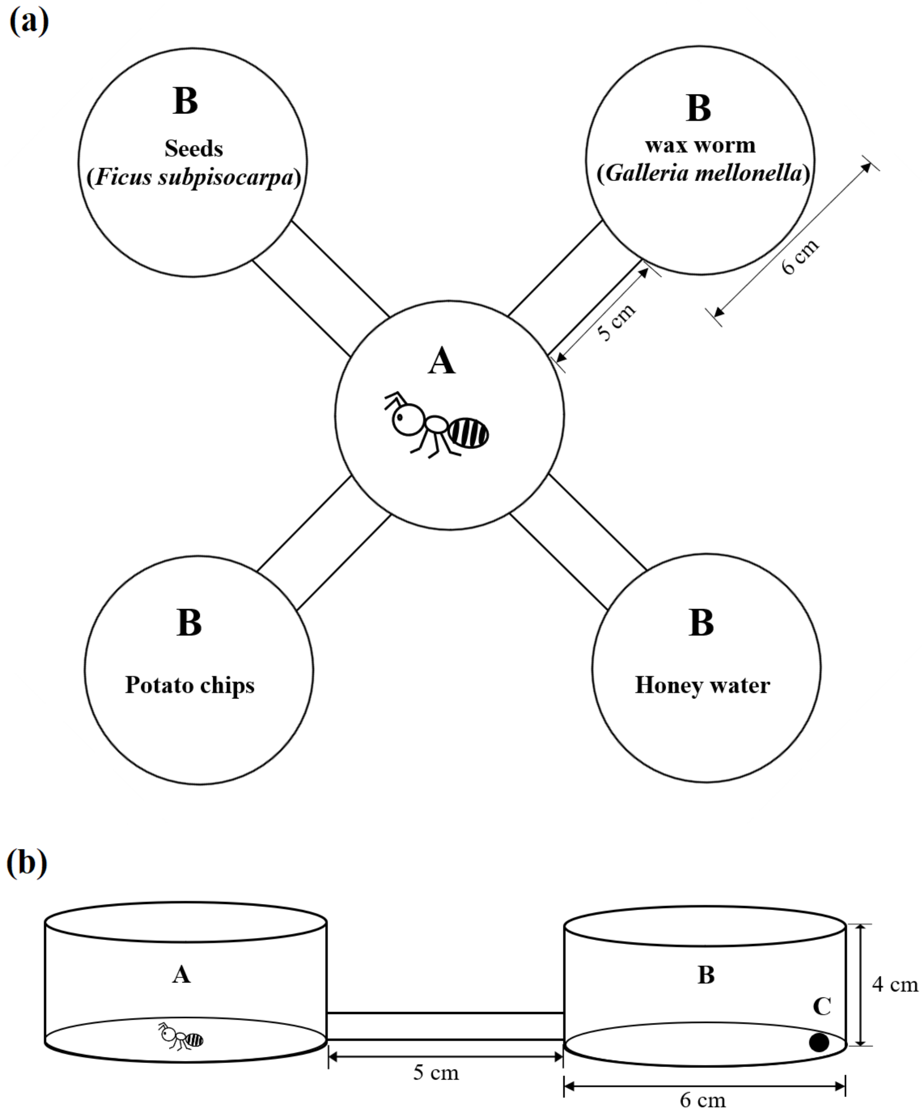

Fig. 1. Experimental set-up. (a) The four-arm maze was utilized to investigate the exploratory behavior of individual workers. The maze consisted of a central plastic container (A; 6 cm diameter × 4 cm deep) connected to four additional plastic containers (B) via Tygon tubes (5 cm length). We randomly placed potato chips, seeds (*Ficus subpisocarpa*), wax worms (*Galleria mellonella* larvae), and 2% honey water in separate containers. (b) One arm of a four-arm maze. The ant begins at the central plastic container (A) as its starting point for exploration. The central plastic container is connected to the plastic container (B) using a Tygon tube, and a food item (C) is placed inside the B plastic container.

First, we collected a group of 10 workers and placed them in a container to acclimate for 30 minutes before beginning the assay. Then, we used a chopstick affixed with a toothpick holding a nylon bristle (from a test tube brush) to collect an individual worker as it climbed the bristle. Subsequently, we positioned the chopstick at the center of the plastic container, allowed the ant to descend onto it (Lai et al. 2022), and observed its exploratory behavior for 5 minutes, as in Hui and Pinter-Wollman (2014). This transfer method could help reduce disruptions for the workers. Workers were discarded if they showed disturbed behavior before their introduction into the center of a four-arm maze. During the assay, observers wore surgical masks to reduce disturbances from workers' exhalation, following a method adapted from Vander Meer and Alonso (2002). Each worker was not returned to the nest afterward but was placed in a separate container. The plastic containers of the four-arm maze were cleaned with 75% ethanol after each test to eliminate any potential pheromone residues left by the workers.

In this assay, we define an exploratory worker as an ant that successfully seeks out and visits food items in the four-arm maze, while a non-exploratory worker is one that does not visit any food items successfully. "Exploratory time" refers to the duration an ant actively searches for and interacts with food sources. We recorded several metrics: the exploratory rate (the ratio of ants that explored the food for each group), exploratory time (the time taken to reach the first food for each ant), the types of food encountered, the number of food items explored for each group, and the dwell time (the duration spent on each food item). A total of 13 groups (130 workers) were tested from each colony.

Group Exploration Assay

To investigate group exploration behavior, we formed two types of groups, each consisting of 10 workers. Each nest contained two such groups, and the workers within each group originated from the same nest. This ensures that each group is homogeneous regarding genetic background and prior social interactions. By maintaining homogeneous groups, we control for potential variability in behavior due to differences in social dynamics between workers from different nests. One type of group (Group of Type A) consisted of individual workers that have undergone individual exploration assays (one-time exploration experience), while the other type (Group of Type B) comprised workers that had not undergone individual exploration assays (no exploration experience). In each trial, a fresh group of 10 workers was introduced into the central chamber, and we observed their navigation through a four-arm maze for 5 minutes. The plastic containers of the four-arm maze contain potato chips, seeds (*F. subpisocarpa*), wax worm (G. *mellonella* larvae), and honey water, as described above. The group exploration assay procedure is identical to that described above for individual exploratory assays. In this assay, we conducted 13 groups for each type (Group of Type A and Group of Type B), resulting in a total of 26 group trials, each involving 260 workers from each nest. We recorded the time taken to reach each type of food by any ant in each trial, and averaged to represent the exploratory time for group exploration. If the food was not reached by any ant in a 5-minute trial, the exploratory time was assigned to 301 seconds.

In this assay, we asked whether the average time spent exploring food by ants with prior experience (Group of Type A) was shorter than that spent by workers without prior experience (Group of Type B). We also examined the average time spent exploring food by individual workers in individual exploration assays and by the same workers in the group exploration assay. After each experiment, workers were moved to a separate container to ensure they were not reused, and were supplied with water and sugar-water *ad libitum* until they naturally expired.

Statistical analyses

The mean values of exploratory rate, the exploratory time, and dwell time were calculated in the individual exploration assay, while the mean exploratory time was calculated in the group exploration assay. Analysis of variance (ANOVA) tests were used to assess if there were differences between nests or among foods. For data that were not normally distributed, nonparametric Kruskal-Wallis tests were used. The Mann-Whitney-Wilcoxon test was used to determine the differences between nests and between groups of types, and the post hoc Dunn's multiple comparison test with Bonferroni correction was used to determine the differences among foods. The frequency of ants visiting among food was examined by Fisher's exact test. All statistical tests were conducted at a significance level of $P < 0.05$ using the software package SAS 9.4 (SAS Institute Inc. 2016).

RESULTS

Individual Exploration Assay

The individual exploration of 130 workers per colony was analyzed, with 74 (the rates of successful exploration: 56.9 ± 26.9%) and 86 (the rates of successful exploration: 66.2 ± 16.6%) exploratory workers observed in Nest 1 and Nest 2, respectively. There was no significant difference between nests (1-way ANOVA; F =1.11, P = 0.3028). Among them, 56.2% (73 out of 130) of the workers in Nest 1 explored a food item, while 64.6% (84 out of 130) of the workers in Nest 2 did the same. One worker from Nest 1 discovered two types of food, and two workers from Nest 2 discovered two types of food. However, 43.1% (56 out of 130) of the workers in Nest 1 did not explore any food, compared to 33.8% (44 out of 130) in Nest 2. Among the types of food discovered, 20.8% of workers in Nest 1 and 13.1% in Nest 2 found a wax worm. Additionally, 10.8% of workers in Nest 1 and 22.3% in Nest 2 found potato chips; 13.1% of workers in Nest 1 and 14.6% in Nest 2 found honey water; and 12.3% of workers in Nest 1 and 16.2% in Nest 2 found seeds (Table 1).

Table 1. The number of individual workers (N) and the time (seconds, mean ± SD) spent exploring the four types of food successfully for the two nests in the individual exploration assay

Food	Nest 1		Nest 2	
	N (%)	Time (seconds)	N (%)	Time (seconds)
Wax worm	27 (20.8)	135.1 ± 70.8	17 (13.1)	182.1 ± 66.1
Potato chips	14 (10.8)	135.8 ± 62.3	29 (22.3)	161.8 ± 74.3
Honey water	17 (13.1)	146.6 ± 70.1	19 (14.6)	178.4 ± 69.1
Seeds	16 (12.3)	173.8 ± 78.4	21 (16.2)	155.7 ± 68.4
The average time*	**74 (56.9)**	**146.2 ± 71.1**	**86 (66.2)**	**168.0 ± 69.7**

*The average time taken by workers to reach the food (regardless of the type of food).

In the individual exploration assay of 130 workers, the average time (seconds, mean ± standard deviation) taken by workers to reach the food (regardless of the type of food) was 146.2 ± 71.1 s (n = 74) in Nest 1 and 168.0 ± 69.7 s (n = 86) in Nest 2 (Table 1). The average time for the workers to explore and reach specific food types was 135.1 ± 70.8 s in Nest 1 and 182.1 ± 66.1 s in Nest 2 for wax worms, 135.8 ± 62.3 s in Nest 1 and 161.8 ± 74.3 s in Nest 2 for potato chips, 146.6 ± 70.1 s in Nest 1 and 178.4 ± 69.1 s in Nest 2 for honey water, and 173.8 ± 78.4 s in Nest 1 and 155.7 ± 68.4 s in Nest 2 for seeds (Table 1). In this assay, there was no significant difference in the time individual workers took to find the food among food and between nests (2-way ANOVA, $F = 1.31$, P = 0.2494). Four types of food were visited with similar frequency (Fisher's exact test, $P = 0.059$). Two-way ANOVA showed that there were significant effects of nest and food on dwell time (i.e., the amount of time workers spent on each type of food) ($F = 4.21$, $P < 0.001$).

The average dwell time that workers from both nests spent on specific food types was as follows: 5.6 ± 5.8 s in Nest 1 and 9.8 ±13.4 s in Nest 2 for wax worms; 14.3 ± 24.8 s in Nest 1 and 15.6 ± 25.2 s in Nest 2 for potato chips; 3.7 ± 5.6 s in Nest 1 and 4.4 ± 7.8 s in Nest 2 for honey water; and 8.7 ± 10.1 s in Nest 1 and 9.8 ± 16.9 s in Nest 2 for seeds (Fig. 2). There was no significant difference in dwell time between nests (Kruskal-Wallis test, χ^2 =1.66, $P = 0.1981$). However, the post hoc Dunn's test indicated that there were significant differences were found between potato chips and honey water in Nest 1 (χ^2 =13.83, $P < 0.01$) and in Nest 2 (χ^2 =17.64, P = 0.001). The results show that workers in both nests spent more time on the potato chips and less time on the honey water.

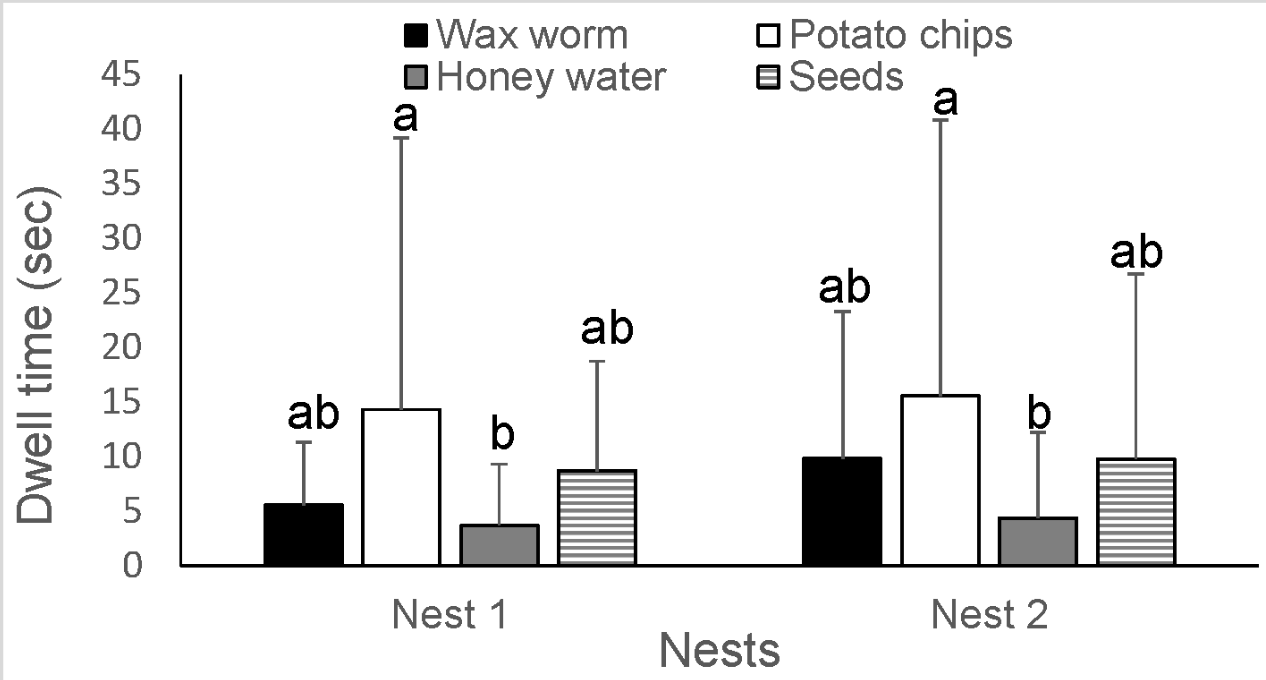

Fig. 2. The average dwell time workers spent on specific food types in the individual exploration assays in both nests. The same letters above standard deviation indicated no significant difference within nest determined using Kruskal-Wallis test, followed by Dunn's post hoc test for multiple comparison at a significance level of 0.05. Wax worm: *Galleria mellonella* larvae; Seeds: *Ficus subpisocarpa* seeds.

Group Exploration Assay

The average time spent exploring the four types of food was compared between workers with experience (Group of Type A) and those without experience (Group of Type B) (Fig. 3). In Nest 1, the average time individual workers with one-time exploration experience (Group of Type A) took to reach the food was 147.9 ± 77.1 s (mean ± SD), and individuals without exploration experience (Group of Type B) was 174.8 ± 36.3 s. In Nest 2, the average time individual workers with one-time exploration experience (Group of Type A) took to reach the food was 172.0 ± 42.2 s, and individuals without exploration experience (Group of Type B) was 105.1 ± 42.8 s. No significant difference between groups was found in Nest 1 (Kruskal-Wallis test, χ^2 =1.85, P = 0.1742), but a significant difference between groups was found in Nest 2 (χ^2 =9.31, P < 0.01) (Fig. 3).

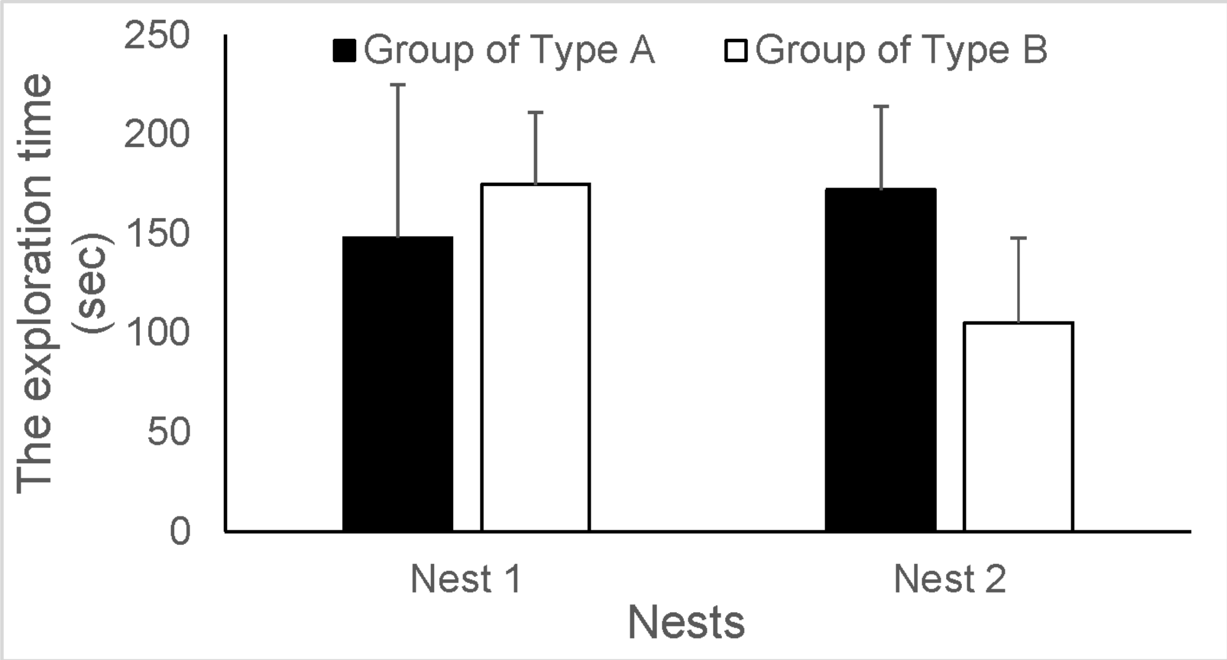

Fig. 3. Comparison of the average exploration time spent by workers on the four types of food between those with and without experience from both nests. No significant difference between groups was found in Nest 1 (Kruskal-Wallis test, χ^2 =1.85, P = 0.1742), but a significant difference between groups was found in Nest 2 (χ^2 =9.31, P = 0.01). Group of Type A, workers with one-time exploration experience; Group of Type B, workers without exploration experience.

During the exploration assay, if a worker ant did not find food, the trial was considered a failure and recorded as 301 seconds. When comparing the average time taken to reach the four food items by workers in the individual exploration assay with the same workers in the group exploration assay, the results indicate that workers in the group were able to find the food more quickly; however, no significant difference was found between individual and group exploration in both nests (Kruskal-Wallis test, χ^2 =3.50 and 0.35, and P = 0.0612 and 0.5554 for Nests 1 and 2, respectively) (Fig. 4). In Nest 1, the average time taken by workers to reach the four food items was 189.9 ± 55.3 s in the individual exploration assay and 147.9 ± 77.1 s in the group exploration assay. In Nest 2, the average time taken by workers to reach the four food items was 189.5 ± 48.6 s in the individual exploration assay and 172.0 ± 42.2 s in the group exploration assay (Fig. 4).

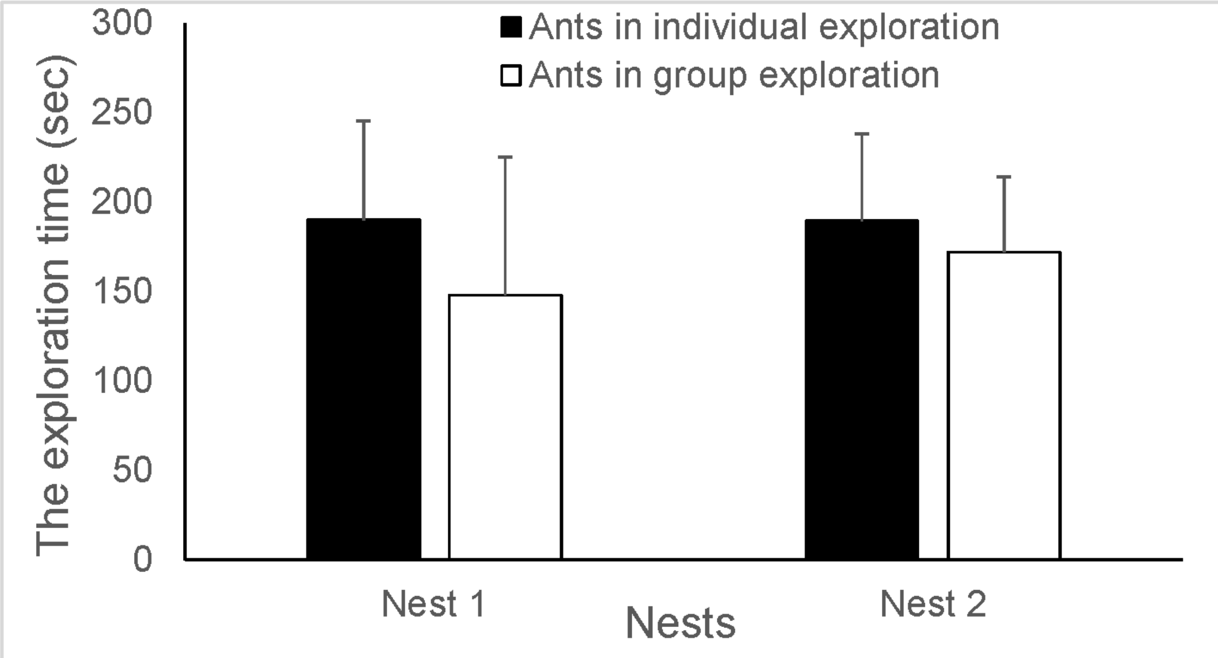

Fig. 4. Comparison of the average exploration time taken by workers to reach the four food items between individual and group exploration assays from both nests. No significant difference was found between individual and group exploration in both nests (Kruskal-Wallis test, χ^2 =3.50 and 0.35, and P = 0.0612 and 0.5554 for Nests 1 and 2, respectively).

DISCUSSION

We investigated the exploratory behavior of *S. geminata* workers in the four-arm maze. In the individual exploration assay, most workers find only one food item. Although some workers failed to explore, more than half could find a food item within 5 minutes. Moreover, there were no significant differences in the proportions of workers that discovered the four types of food. This study does not investigate the food preferences of workers; however, in the individual exploration assay, workers spent the most time on the potato chips, followed by the seeds, and the least time on the honey water. This suggests that the nutritional content may affect how long workers remain at a specific food source. *Solenopsis* spp. preferred protein-rich foods such as hot dogs and tuna, and oily foods like potato chips (Bao et al. 2011; Vogt et al. 2003). Additionally, *S. geminata* workers harvest seeds from numerous plants (Lai et al. 2018). In contrast, honey water, being a liquid, may be quicker to consume, leading to less time spent at the food source. The behavior of staying longer at specific food sources may relate to the colony's foraging strategies. Ants tend to gather high-energy foods to ensure they collect adequate resources for the colony's needs. Understanding how fire ants respond to different food sources can provide insights into their foraging adaptability and resource competition in invaded ecosystems.

In this study, the average time it took for workers from Nest 2 to reach the food was slightly longer than that for workers from Nest 1. However, a greater number of workers from Nest 2 successfully reached the food compared to those from Nest 1, despite no significant difference in the rates of successful exploration between the two nests. The previous study shows that *S. geminata* workers display varying search patterns in unexplored areas (Lai et al. 2022). Their search patterns may influence the exploration time among workers. Thus, variations in search patterns exhibited by workers in their exploration behavior may influence exploratory time (Lai et al. 2024). Our results suggest that workers within nests exhibit varying degrees of exploratory behavior, as observed in both this study and prior research (Hui and Pinter-Wollman 2014). Differences in exploration behavior exist among individual workers and different colonies within the same species. The behavioral variation among individual workers could result from the information they receive, their interactions on both personal and group levels, and their learning abilities (Kolay et al. 2020).

Variation in exploratory time among colonies reveals differences that may affect their foraging activity and efficiency (Gordon et al. 2011). In Nest 1, groups of workers with prior exploration experience (Group of Type A) were faster to find foods than those without such experience (Group of Type B). However, in Nest 2, the opposite was observed. In the group exploration assay, workers did not tend to follow each other, regardless of whether they had individual exploration experience. This phenomenon is similar to what was observed in Argentine ants (Mahavni et al. 2019). It is still unknown whether each worker in the group contributes equally to determining group-level behavior. We speculate that among these foraging workers, some are experienced foragers, while others have less experience. Even if a group includes experienced individuals, it may also contain members with low exploratory tendencies or non-exploratory members (Hui and Pinter-Wollman, 2014; Madrzyk and Pinter-Wollman, 2022). This could explain why the experienced group (Group of Type A) takes longer to explore than the group without experience (Group of Type B) in Nest 2. Their level of experience and exploration may influence their exploration speed. Furthermore, Mahavni et al. (2019) propose that the behavior of individual workers may differ from that of groups. They seem to explore directions randomly, regardless of whether they are alone or in groups. This phenomenon, also observed in our previous study, shows that the exploratory behavior of individual workers tends to involve randomly searching novel areas (Lai and Chao 2021; Lai et al. 2022, 2024). Therefore, it is also possible that when an individual randomly discovers food, it prompts others to find it more quickly.

At the colony level, behavioral variation among colonies has been studied in different ant species. In *S. invicta* colonies, there is variation in foraging behaviors (Bockoven et al. 2015). Other work has shown that colonies of *L. niger* with higher levels of exploratory activity are able to exploit food sources more rapidly (Pasquier and Grüter 2016). Workers exhibit significant behavioral variation both within and among colonies (Jandt and Gordon 2016), which substantially influences the collective behavior of the colony (Hui and Pinter-Wollman 2014). Our work showed that varying degrees of exploration behavior existed among individual and group workers, potentially impacting foraging efficiency and resource utilization. Furthermore, variations in exploratory behavior may enable some colonies or species to establish themselves more successfully in invaded areas than others (Hui and Pinter-Wollman 2014).

Research on social insect colonies has demonstrated that individual behaviors and interactions among members can influence group behavior (Beverly et al. 2009; Jandt et al. 2014). As the behavior of individual ants may be regulated by the actions of others, accordingly the entire group may be affected by the actions of a few (Conradt and List 2009). Here we found that the average time workers reached the food during group exploration was shorter than that of the individual exploration test. This suggests that group workers may find food more efficiently than individual workers. When a group includes exploratory individuals, it may discover new food sources faster and recruit others to the food source (Hui and Pinter-Wollman 2014; Madrzyk and Pinter-Wollman

2022). We are unsure whether individuals within a group exhibit behavioral heterogeneity. Additionally, it remains unclear whether exploratory individuals influence less exploratory or non-exploratory individuals within the group and how that affects overall efficiency. However, behavioral differences among workers within and among the colony have been demonstrated (Sih et al. 2004; Maák et al. 2021; Trigos-Peral et al. 2023).

Herein we investigated *S. geminata* workers in the group were able to find the food more quickly than individual workers. Previous individual experiences can influence differences in group behavior. Although it is unclear exactly how behavioral variation at the individual level leads to differences at the group level. Maintaining behavioral variation within a colony is essential for a rapid response to environmental changes (Jandt et al. 2014). Previous studies have found that *S. geminata* foragers can quickly locate food and recruit many workers upon detecting it. They are significantly faster at recruiting and controlling a food source (Chen et al. 2014). As an invasive ant species, they easily adapt to disturbed habitats, enabling them to outcompete and gradually replace native ants. This process alters the diversity of native ant communities and significantly disrupts the balance of local ecosystems (Morrison, 2000). For invasive species facing the challenges of a new environment, quickly obtaining food resources is crucial for their survival and reproduction. Future studies should investigate how environmental conditions, such as resource availability or competition pressure, and social interactions, like the distribution of highly exploratory individuals within the group, affect the overall exploratory behavior of *S. geminata* colonies.

CONCLUSIONS

In this study, we investigated the individual and group exploration behaviors of *S. geminata* workers. There were significant effects of nest and food source on dwell time in the individual exploration assay, with workers spending more time on potato chips and less time on honey water. To compare the average time spent exploring food items between groups of workers with and without experience, we found no significant difference in Nest 1. However, a significant difference was observed in Nest 2. The results showed that group workers found the food more quickly, although no significant difference was observed between individual exploration assays and the same workers in group exploration assays. Behavioral variation among workers at both individual and group levels is essential for rapid responses to environmental changes in their invaded regions. We proposed that differences in exploratory behavior among individual workers and groups, both within and between colonies, could affect foraging efficiency and resource utilization.

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Both authors have read and approved the final manuscript.

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Availability of data and materials: Raw data can be obtained upon request.

Consent for publication: Not applicable.

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