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Exploring a Common Strategy of Insect Goal-Oriented Behavior using Sensory Substitution

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Abstract: Sensory modalities used for animal orientation, such as vision, audition, and olfaction, differ in their physical properties, which may have influenced the evolution of distinct behavioral strategies for each sense. However, it remains unclear whether animals use separate strategies for each sensory modality or share a common goal-oriented strategy. This study focuses on odor-, light-, and sound-source orientation behaviors in insects and develops a closed-loop system that integrates an odor- or light-sensing mobile robot with the auditory navigation (phonotaxis) of a cricket. The system consists of a mobile robot that acquires sensory signals from the real world and a cricket placed in an auditory virtual reality, which remotely controls the robot in response to substituted auditory stimuli. By substituting the auditory input of a cricket with visual or olfactory cues, this system provides a direct method for investigating whether a common strategy underlies goal-directed behaviors across different sensory modalities.

Keywords: Search strategy, Mobile robot, Virtual reality, Sensor, Biomimetics

1. INTRODUCTION

Navigation is essential for survival across a wide range of organisms, from bacteria and insects to mammals, all of which possess mechanisms for localizing their destinations. Even small insects, such as desert ants and honeybees, have been shown to integrate odometry through vector integration and visual landmark information for localization [1, 2]. Therefore, the seemingly simple behaviors of insects provide valuable models for uncovering the fundamental strategies for various navigational tasks. A wide range of localization behaviors based on visual, auditory, olfactory, and other sensory modalities has been studied with the goal of applying these mechanisms to mobile robots. However, it remains unclear whether insects employ distinct behavioral strategies depending on the spatiotemporal characteristics of each sensory modality, that is, different behaviors arising from separate behavioral modules, or whether a common underlying strategy gives rise to behavioral diversity, with variations in sensory input dynamics shaping the observed behaviors (Fig. 1).

Taxis is a fundamental mechanism of navigation in which organisms move toward or away from a stimulus, depending on its intensity. For example, chemotaxis in unicellular organisms such as *Escherichia coli* involves detecting chemical concentration gradients: the organism continues moving straight when the gradient increases toward the preferred chemicals and changes direction when the gradient decreases [3]. As many multicellular organisms are bilaterally symmetrical, the integration of left-right information plays an important role in localization behavior. For stimuli, such as light and sound, it is fundamental to move toward stronger inputs using circuits in which the left and right signals interact, as exemplified by Braitenberg vehicles [4]. A circuit model based on the left-right sound pressure difference has also been implemented in robots to replicate the phonotaxis behavior observed in crickets [5]. However, chemotaxis is limited to relatively static environments in which stable sensory gradients are present. In contrast, spatially discretely distributed information, such as odor cues [6], requires not only movement toward a goal but also exploratory behavior to reacquire lost information. Various behavioral strategies for odor source localization have been reported in different animal species. A basic strategy involves moving straight along the odor plume while the odor is detected. However, when the odor is lost, animals shift to exploratory behaviors characterized by frequent turns and changes in direction [7]. Thus, odor source localization appears to involve more specialized mechanisms than localization based on other sensory stimuli. Nevertheless, based on extensive knowledge of

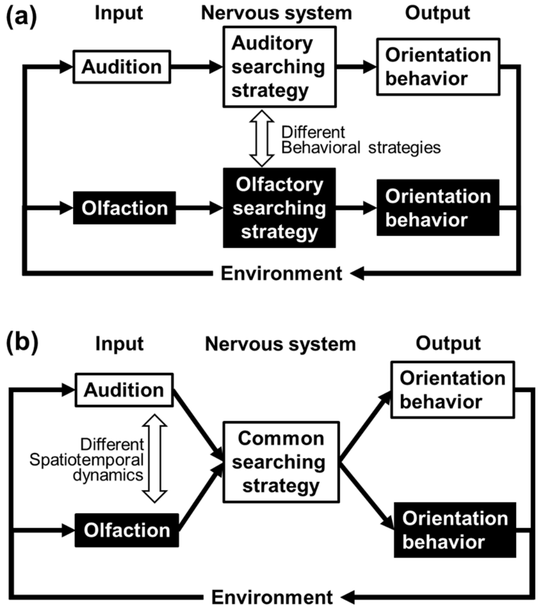

Fig. 1 Hypothetical mechanisms behind goal-oriented behaviors.
(a) Each sensory input independently activates corresponding behavioral modules. (b) Different orientation behaviors emerge from a common searching strategy.

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† Noriyasu Ando is the presenter of this paper.

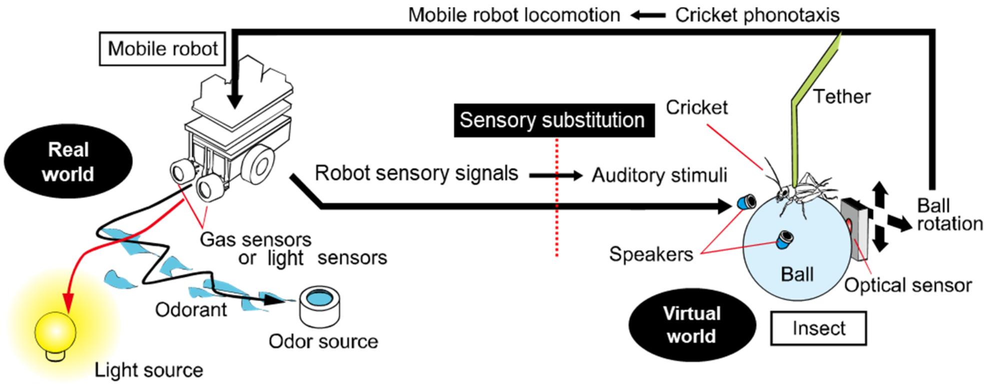

Fig. 2 System design of the insect-driven mobile robot with sensory substitution.

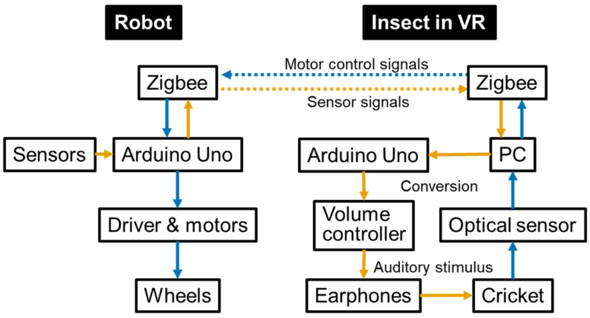

Fig. 3 System diagram.

insect brain structure and function, the central complex, an area analogous to the human brainstem which has become increasingly well understood in recent years, is believed to play a key role in generating reciprocal steering during exploratory behavior. This region is considered a shared neural substrate for localization to odor sources as well as auditory and visual targets [8]. These findings suggest the existence of a common neural circuit and strategy underlying localization behaviors across different sensory modalities.

Behavioral strategies can be compared by observing the behavior of living organisms, constructing behavioral and neural circuit models, and implementing these models in mobile robots. However, the sensory-motor systems of living organisms are not yet understood, and current models do not perfectly replicate these systems. In this study, instead of relying on models, an actual insect is used as the robot controller, and sensory substitution is applied to arbitrarily combine the sensory-motor system of a living organism operating in a virtual environment with that of a mobile robot operating in the real world. This approach aims to determine whether the two systems share a common behavioral strategy. The system enables cross-modal sensory integration between robots and insects, and can help reveal whether a navigation strategy based on a single sensory modality can be generalized to search and localization tasks involving other sensory modalities.

2. SYSTEM DESIGN

In this study, the sound localization behavior of female crickets in response to a male song [9] was employed as a candidate model for a common exploratory strategy. Accordingly, it was investigated whether other sensory modalities, specifically light and odor, could substitute auditory stimuli within the information flow governing exploratory behavior, as illustrated in Fig. 1. Therefore, an experimental system was designed comprising the following components: (1) a mobile robot that localized a target in a real environment, (2) onboard sensors that acquired sensory information, (3) a system that converted the acquired information into auditory stimuli to elicit localization behavior in crickets, and (4) a mechanism to measure the responses of crickets and remotely control the robot based on these behaviors (Fig. 2).

3. CLOSED-LOOP SYSTEM LINKING AN INSECT AND ROBOT

3.1 Mobile robot

The two-wheeled mobile robot consisted of an educational two-wheeled robot body (e-puck, EPFL, Lausanne, Switzerland), a controller board (Arduino Uno), a wireless communication board (XBee, Digi International, Hopkins, MN, USA), and a motor driver board (STA457C, Sanken Electric, Niiza, Japan) (Figs. 3 and 4(a, b)). To acquire stereo light or olfactory information, two photodiodes (BPW21, ams OSRAM, Premstätten, Austria) or gas sensors (CH-ETiXP, New Cosmos Electric, Osaka, Japan) were mounted on an amplifier board located on the bottom layer of the robot body with a left-right separation of 10 mm. The acquired sensory signals were sampled at 60 Hz using an Arduino and transmitted to a PC via a Zigbee (Fig. 3). To improve the signal transmission speed in bidirectional communication between the robot and the auditory virtual reality (VR) system, the acquired left and right sensor values were downscaled to 4-bit representations and packed into a single 8-bit byte. The rotational and translational velocities of the robot were controlled using motor commands based on cricket locomotion (see

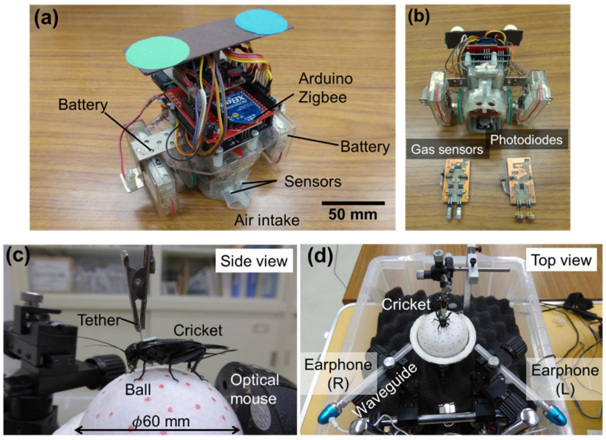

Fig. 4 Experimental system.

(a) Two-wheeled mobile robot. (b) Sensor boards. (c) Tethered cricket on a trackball. (d) Auditory VR.

Section 3.2) and at a control frequency of 60 Hz. At this frequency, the maximum number of steps for the stepper motors was six, which could be represented using 4-bit values. These were also packed into a single 8-bit byte to transmit the left and right motor control signals. The maximum angular and translational velocities of the robot were 94°/s and 48 mm/s, respectively.

3.2 Auditory VR

A diagram of the auditory VR system is shown in Fig. 3. Adult female crickets (*Gryllus bimaculatus*) aged two to three weeks were used in this study. The dorsal thorax of each cricket was secured with a fixture, and the insect was placed on an air-supported polystyrene ball (Fig. 4(c), φ 60 mm). The ball rotation was tracked using an optical mouse (MA-LSMA4BK, Sanwa Supply, Okayama, Japan), and the displacement data along the x-axis (angular velocity for left or right turns) and y-axis (forward or backward translational velocity) were recorded using a PC at a sampling rate of 60 Hz. A conspecific male calling song, which reliably elicited sound source localization behavior in females even within a virtual environment [10], was used as an auditory stimulus. The auditory stimulus was delivered through a pair of stereo earphones (H310, Monotaro, Osaka, Japan) positioned in front of the cricket, angled at 45° relative to its body axis, to target the auditory organs located on the left and right forelegs. To ensure highly directional stimulation, waveguides were attached to the earphones and positioned close to the cricket (Fig. 4(d)). The entire setup was enclosed with sound-absorbing sponges to minimize the external auditory noise, visual distractions, and unwanted sound reflections within the apparatus.

To elicit insect behavior through sensory stimulation, the stimulus must exceed a certain intensity, known as the behavioral threshold, for the insect to recognize it as a key stimulus. However, the translation of one sensory modality into another remains unclear. In this study, because the output voltages of the sensor units increased linearly with the logarithmic intensity of the sensory inputs (illuminance or gas concentration) within the operating ranges, these voltage signals (0–15) were linearly mapped to the sound pressure levels of the calling song stimulus. To maintain phonotactic activity during the experiment, a minimum sound pressure of 45 dB SPL, approximately at the behavioral threshold [10], was uniformly assigned to lower sensor values ranging from 0 to 6. Sound pressures from 45 to 75 dB SPL, covering the range from just below the behavioral threshold for phonotaxis to the maximum intensity near a singing male [10], were linearly mapped to higher sensor values ranging from 6 to 15 (Fig. 5(a)). The sound pressure of the auditory stimulus was regulated using a volume controller (PGA2311, Texas Instruments, TX, USA). Sensor signal acquisition, insect locomotion tracking, robot control, and auditory virtual reality presentation were implemented using a custom program written in Processing software.

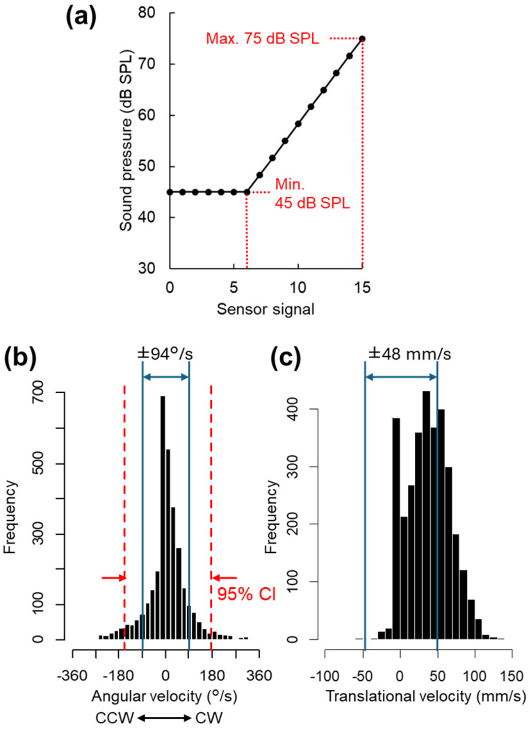

Fig. 5 Conversion of sensor output to sound stimulus and locomotor characteristics of crickets.

(a) Sensor output to sound pressure conversion. Histograms of the turn angular velocity (b) and translational velocity (c) of a cricket.

3.3 System evaluation

To enable crickets to search for stimulus sources using sensory cues acquired by the robot in real-time from the physical world, the system latency was minimized. In the proposed setup, the time delay between the sensory input of the robot and delivery of the auditory stimulus (indicated by the orange arrows in Fig. 3) was a single step (16.7 ms). By contrast, the delay from the cricket movement (as detected by the optical sensor) to the

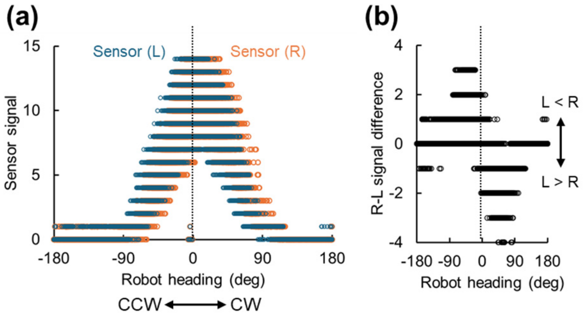

Fig. 6 Light reception relative to the heading of the robot.

(a) Directionality of photodiode signal intensity on each side (L: left, R: right). (b) Bilateral difference in sensor signals (R – L)

initiation of the robot movement (indicated by the blue arrows in Fig. 3) was approximately five steps (83.3 ms). Although it remains unclear whether a total latency of approximately 100 ms is sufficiently short to elicit natural behavior, it is comparable to that of similar silk moth-driven mobile robot systems (approximately 130–200 ms) [11].

Based on locomotion data recorded during cricket phonotaxis, it was found that the maximum angular and translational velocities of the robot were insufficient to replicate those of crickets within each sampling/control cycle (16.7 ms @ 60 Hz). Figs. 5(b) and (c) show histograms of the angular and translational velocities of the cricket per cycle during phonotaxis (the same dataset as in Fig. 7), indicating that the ranges of velocities achievable by the robot (±94°/s for angular velocity and ±48 mm/s for translational velocity, limited by the number of motor steps per control cycle) were below those exhibited by the crickets. To address this issue, the differences between the target angular and translational velocities, derived from the locomotion of the cricket, and the actual motor steps executed in each cycle were accumulated. These accumulated differences were then compensated for in subsequent cycles when the motors could accommodate additional steps.

The photodiodes, with a directional selectivity of 55°, provided the robot with directional sensitivity toward the light source (Fig. 6(a)). The 10 mm left-right separation generated a differential sensor signal between the left and right photodiodes, depending on the heading of the robot relative to the light source (Fig. 6(b)).

4. SOURCE LOCALIZATION TEST

4.1 Localization test conditions

Localization tests toward the stimulus source were conducted on a flat desk (W 1250 × D 900 mm), with the robot starting 900 mm from the source. Under these experimental conditions, the gas sensors failed to capture a sufficient dynamic range of odor (ethanol)

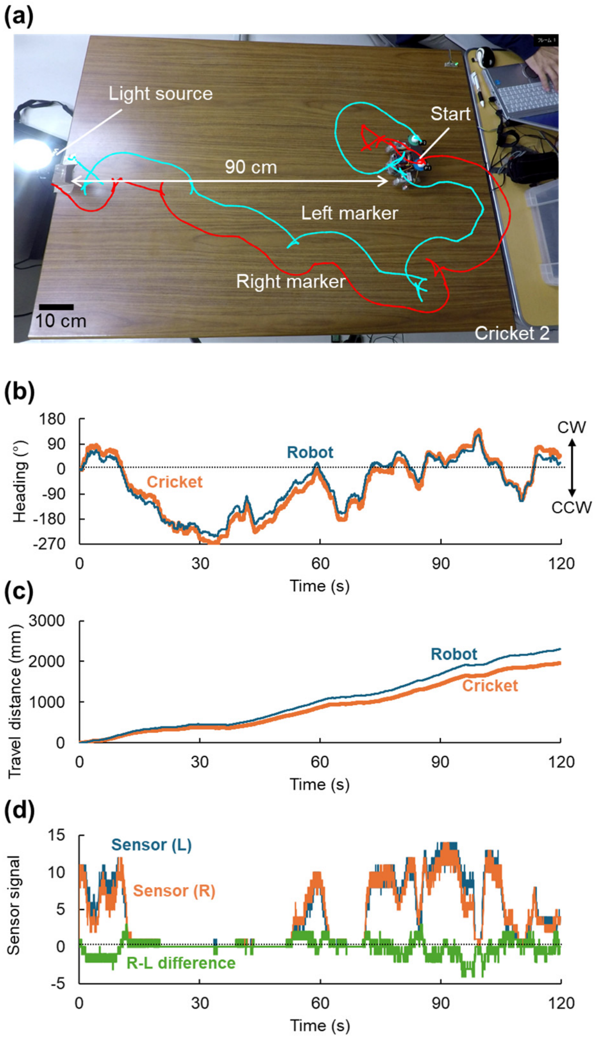

Fig. 7 Localization to a light source.

(a) Representative robot trajectory toward the light source. (b) Robot heading over time. (c) Robot travel distance. (d) Acquired sensor signals.

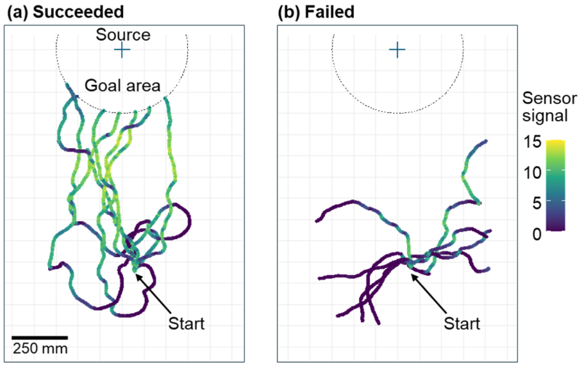

Fig. 8 Robot trajectories in localization tests.

(a) Succeeded trials conducted by seven crickets, (b) failed trials (nine in total) conducted by five crickets.

concentrations, presumably because of inadequate exhaust. Alternatively, a light source (white LED lamp) and photodiodes were used to investigate the feasibility of this approach. Nine crickets were used and localization tests were conducted up to three times per cricket until successful localization of the light source was achieved. Success or failure was determined based on whether the robot reached within 300 mm of the light source (designated as the goal area in Fig. 8). The behavior of the robot was recorded using a USB camera, and its trajectory was extracted using image processing software (DIPP-Motion V, Ditect, Tokyo, Japan).

4.2 Results

A point light source generated a constant gradient of light intensity from the source, similar to the attenuation of the sound pressure level with the distance from the sound source and the continuous concentration gradient formed by the diffusion of odorants. This contrasts with the discontinuous distribution of odorants typically observed in turbulent flows. Nevertheless, owing to the narrow directivity (Fig. 6) of the photodiode and frequent turning of the cricket, the sensor signals received by the robot fluctuated between zero and near the maximum value as the robot rotated (Fig. 7). Consequently, the temporal profile of the received light became intermittent, partially simulating the discontinuous sensory input found in the odor distributions (Fig. 7(d)).

Of the nine crickets used in the experiment, seven that exhibited sound localization behavior could localize the robot to the light source (Fig. 8 and Table 1). Cricket phonotaxis consists of simple reflexive behaviors [12]. Similar to Braitenberg vehicle 2b [4], crickets steered toward the side with the higher sound pressure. However, as mentioned above, the received light signals were intermittent because of the movement of the robot, and the robot may have had to explore to recontact the light cues, such as zigzagging turns observed in odor tracking behavior, to localize the light source. In some successful trials, the robot reoriented toward the light source even with a lower sensor input (Figs. 7 and 8, with darker colors in the trajectories around the start point). These results suggest that the phonotaxis of the cricket is not a simple reflexive steering but may have additional behavioral strategies to enhance the redundancy of navigation against the spatiotemporal variance of sensory stimuli from the real world.

Table 1 Results of light source localization tests in nine crickets.

	Localization time (s)		
Cricket	Trial 1	Trial 2	Trial 3
1	53.2	–	–
2	Failed	103.5	–
3	Failed	96.0	–
4	70.7	–	–
5	Failed	Failed	Failed
6	Failed	21.8	–
7	28.4	–	–
8	Failed	Failed	Failed
9	25.0	–	–

5. CONCLUSION

This study proposed the use of sensory substitution to investigate the existence of a common goal-oriented search strategy across different sensory modalities. This approach is expected to contribute to the development of search robots that are capable of detecting targets using multiple types of sensory information with a simple configuration. Therefore, a closed-loop system was developed that integrates an odor- or light-sensing mobile robot with the auditory navigation (phonotaxis) behavior of crickets. The results of the light source localization tests suggest that insects may employ a shared goal-oriented behavioral strategy across different sensory modalities, as phonotactic behavior remained functional even when driven by substituted stimuli such as light or odor.

Combining a physical mobile robot, rather than a simulation model, with an insect offers the advantage of enabling tests with time-varying sensory inputs from real world environments. However, the use of a physical robot also introduces limitations owing to differences in body size, sensor response, and control delays between insects and robots. Moreover, sensory stimuli from the real environment hinder precise quantitative control. Therefore, to explore the potential common search strategies that emerge from the diverse spatial and temporal dynamics of sensory inputs, integrating insects with simulation-based environments should not be excluded. Utilizing simulated models in virtual environments, along with validation using physical robots in real world settings, will further facilitate the investigation of shared principles underlying animal search behaviors. Building on this present study, future work will involve conducting odor source localization experiments to further examine the potential common mechanisms underlying sensory-driven goal-directed behavior.

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