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Developing a multisensory integration model to achieve odor source localization in complex environments

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Abstract: In this study, we focused on a female localization behavior of a male silkmoth with the aim of realizing an engineered odor source localization. The male silkmoth has the ability to detect a sex pheromone (Bombykol) emitted by the female and to localize the female. To analyze this ability, we used a virtual reality (VR) framework designed for an insect. This framework allows the provision of controlled multisensory stimuli and measures behavioral responses under various environmental conditions. Behavioral data obtained through this framework were analyzed to assess how multisensory input affects adaptive localization. Based on the results of this analysis, we developed a multisensory integration model for odor source localization in complex environments.

Keywords: Male silkmoth, Odor source localization, Multisensory integration model

1. INTRODUCTION

Localization is an essential behavior of living organisms, including humans. Organisms achieve localization by using various types of information obtained from the environment, such as vision, odors, and magnetic fields. In particular, organisms universally localize by using odors because odors are superior to other environmental stimuli in terms of persistence and diffusion [1]. Previous studies [2, 3] have conducted experiments to investigate the exploratory behavior of organisms that dominantly use odors, but most of these experiments have been conducted in environments where there are no obstacles that inhibit the diffusion of odors. However, in real environments, there are many obstacles that complicate odor diffusion, and organisms achieve localization in such complex environments. In order to investigate how organisms adjust their behavior in environments with complex odor diffusion, it is necessary to measure the relationship between sensory stimulus input and behavioral output with high precision. Therefore, in this study, we attempted to analyze the adaptive behavioral changes of organisms in complex environments by using a virtual reality (VR) framework for an insect [2].

In this study, we focused on a female localization behavior of a male silkmoth (*Bombyx mori*) [3]. The male silkmoth has the ability to detect a pheromone (Bombykol) released by the female and to localize the female, the odor source, by walking. This ability is maintained even under complex environmental conditions, such as the presence of obstacles and turbulence in air currents, suggesting a high degree of adaptability to environmental changes. This suggests that the silkmoth may integrate multisensory stimuli, such as visual and wind stimuli, in addition to odor stimuli, and flexibly adapt to a variety of environments. To analyze this adaptability, we used a VR framework for an insect to expose the silkmoth to various environmental conditions and measured the adaptive behavior of the silkmoth during the encounters. From the measured behavioral data, we analyzed how multisensory stimuli affected the silkmoth's adaptive behavior. Based on the analysis results, we developed a multisensory integration model that can realize Odor Source Localization (OSL). In addition, we conducted comparative verification through simulations between this model and a conventional OSL model [2].

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2. VR EXPERIMENTS USING SILKMOTHS

2.1. Experimental conditions

We used the VR framework for an insect that provides odor, visual, and wind stimuli to measure the behavioral modulations of the silkmoth during the female localization with multisensory input. This framework is a closed-loop system of a behavior measurement device and a virtual environment.

The framework connects the behavior measurement device equipped with a multisensory stimulus system to a virtual environment built on a PC. In addition, the sensory stimuli and behavior data of the insect on the device and the insect in the virtual environment are synchronized with each other, and the behavior data and the timing of stimulus provision can be obtained as time-series data while the insect is on the device. Fig. 1 shows the outline of the VR framework. The behavior of the insect on the device is reflected in the virtual insect. As the virtual insect moves in the virtual environment, the environmental information provided to the device also changes. Thus, the VR framework for an insect is a system that enables the insect to virtually perform OSL. In the vir-

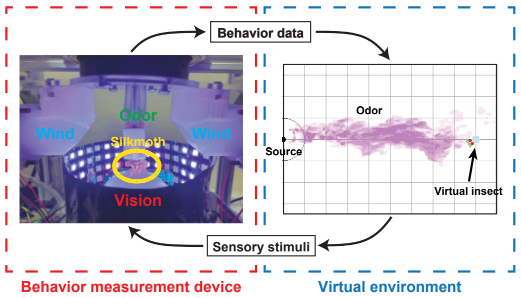
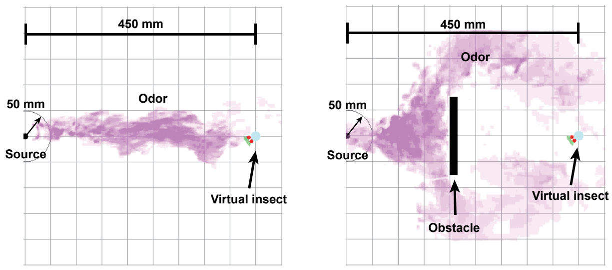


Fig. 1 Relationship between the behavior measurement device and the virtual environment



(a) Open (b) Obstacle

Fig. 2 Experimental conditions for the virtual environment

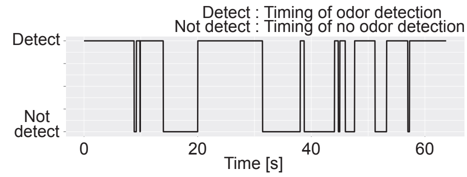
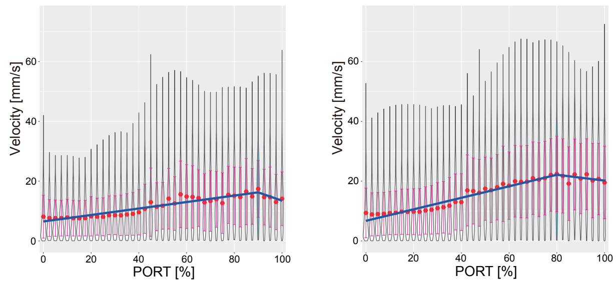


Fig. 3 An example of temporal changes in odor reception



(a) Open (b) Obstacle

Fig. 4 Relationship between the PORT and the translational velocity of silkmoths

tual environment, odor plumes are emitted from the odor source, and if the antennae of the virtual insect enter these plumes, pheromones are emitted to the insect on the device. Assuming that wind blows from the direction of the odor source, the direction of wind stimulation applied to the insect on the device is adjusted according to the posture of the virtual insect in the virtual environment. Furthermore, by providing optical flow in the opposite direction to the insect's rotation, the system creates an illusion of a moving landscape.

In this study, we conducted experiments in two virtual environments: one with no obstacles (Open) and the other with an obstacle (Obstacle). Fig. 2 shows the actual appearance of virtual environments. The experimental conditions in the virtual environment were set as follows:

- Wind stimulation at $1.0\,\mathrm{m/s}$ from the direction of the odor source
- Optical flow at $1.0\,\mathrm{Hz}$ in the opposite direction of the silkmoth's rotation
- Pheromone emission from the odor source at $1.0\,\mathrm{Hz}$
- Time limit of $300\,\mathrm{s}$
- Goal within $5\,\mathrm{cm}$ radius of the odor source
- A total of 30 behavioral experiments were conducted under each environmental condition

2.2. Analysis of experimental data

To investigate the effects of multisensory stimuli on the adaptive behavior of silkmoth, we analyzed the data obtained from VR experiments. A previous study [4] has shown that a causal relationship exists between the movement of the silkmoth and the time of odor reception. In this study, we focused on the Percentage of Odor Reception Time (PORT) to analyze the silkmoth velocity modulation. The PORT is an index that indicates how long the silkmoth has been receptive to the odor in the past T seconds as a percentage. Fig. 3 shows an example of temporal changes in odor reception. Expressing the graph in Fig. 3 as Eq. (1), the PORT can be calculated using Eq. (2). In addition, an exhaustive search for the optimal value of T was conducted. We found the strongest correlation between silkmoth velocity and temporal changes in PORT when $T = 4/3$.

$$O(t) = \begin{cases} 1 & (\text{Detect}) \\ 0 & (\text{Not Detect}) \end{cases} \tag{1}$$

$$\text{PORT} = \frac{100}{T}\int_{t=i}^{i+T} O(t)\,dt \quad \begin{cases} i = 1, 2, 3, \ldots, T_{\text{end}} \\ T_{\text{end}} : \text{OSL success time} \end{cases} \tag{2}$$

Fig. 4 shows the analysis results of the relationship between the PORT and the translational velocity of silkmoths in the two environments using a violin plot. The red dots are the mean values of the translational velocity for each PORT value, and the red lines are the standard deviations. The blue line is the curve that approximates the mean within the standard deviations. From Fig. 4, it is clear that in both environments, the silkmoths modulate their velocity according to PORT. Moreover, there was not much difference in the way the silkmoths changed their velocity with or without an obstacle.

3. MODELING AND PERFORMANCE VERIFICATION

3.1. Developing an OSL model

Based on the analysis results, we developed a new OSL model. When silkmoths detect the odor, they repeat the three states of Surge, Zig-zag, and Loop to perform

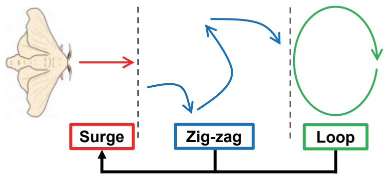


Fig. 5 Female mating behavior of silkmoths

OSL behavior. Fig. 5 shows this silkmoth movement. We modeled the silkmoth movement and developed a PORT model (proposed model) in which the velocity of the silkmoth was modulated as shown by the blue line in the analysis results in Fig. 4. In addition, in order to compare and verify the effectiveness of the PORT model in simulations, an SZL model (conventional model) was used in which the velocity of the silkmoth was fixed to the average velocity calculated from the data of VR experiments using silkmoths.

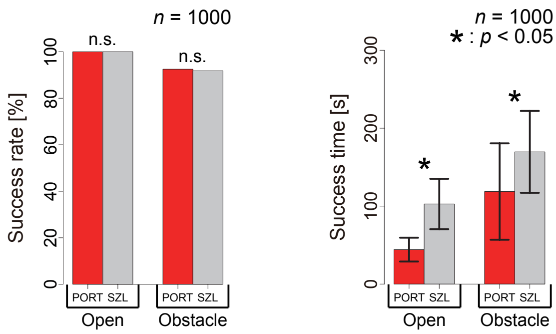
3.2. Simulation results

To verify the effectiveness of the PORT model developed in this study, we compared it with the conventional SZL model in terms of OSL success rate and OSL success time using simulations. The conditions of the virtual environment used in the simulations were set up in the same way as in the VR experiments, and 1,000 trials were conducted for each model ($n = 1000$). Fig. 6(a) shows the results of the OSL success rate, and Fig. 6(b) shows the results of the OSL success time. In the figures, the red bars indicate the simulation results for the PORT model and the gray bars for the SZL model.

As shown in Fig. 6(a), Fisher's exact test revealed no significant difference in OSL success rates between the two models in both environmental conditions (n.s.). On the other hand, as shown in Fig. 6(b), Welch's t test indicated that the PORT model had significantly shorter OSL success time than the SZL model in both environmental conditions (*, $p < 0.05$). These results confirm that the PORT model has higher OSL performance than the SZL model. This may be due to the fact that the silkmoths increase their velocity as the value of PORT increases, moving quickly and reliably toward the odor source, and that they modulate their velocity to avoid deviating from the odor stream by decreasing their velocity near the odor source where PORT approaches 100%.

4. CONCLUSION

In this study, we used the VR framework for an insect to measure and analyze adaptive behavioral changes in silkmoths in complex environments. The analysis results indicate that the silkmoths are able to achieve Odor Source Localization (OSL) regardless of the presence or absence of obstacles by modulating their velocity according to the Percentage of Odor Reception Time (PORT). Furthermore, based on the results of this analysis, we developed a multisensory integrated OSL model and compared the effectiveness of this model with a conventional model using simulations. The simulation results showed



(a) OSL success rate (b) OSL success time

Fig. 6 Quantitative evaluation of simulation results

that the proposed model has higher OSL performance than the conventional model. This may be due to the fact that the silkmoths increase their velocity as the value of PORT increases, moving quickly and reliably toward the odor source, and that they modulate their velocity to avoid deviating from the odor stream by decreasing their velocity near the odor source where PORT approaches 100%.

It is difficult for simulations to completely reproduce the complex odor diffusion and wind flow unique to real environments, including turbulence. Therefore, in the future, we plan to conduct an actual experiment using an autonomous OSL robot to verify whether the model proposed in this study is effective in a real environment. In the experiment, the proposed model and the conventional model will each be incorporated into the robot, and their performance will be compared and verified.

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