Modification in Command Neural Signals of an Insect's Odor Source Searching Behavior on the Brain-Machine Hybrid System

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Abstract. To investigate the adaptive behavior and the underlying neural mechanisms, we focused on the insect's brain and developed the brain-machine hybrid system. The hybrid system is a mobile robot controlled by recorded neural signals related to steering motor pattern on the robot. We manipulated the motor output of the robot to introduce the rotational disturbances to the hybrid system and acquired the compensatory neural activities. Moreover, we manipulated the motor pattern of the robot during odor source orientation behavior. The moth on the robot maintained the angular velocity and succeeded in odor source localization by modifying the neural activities.

Keywords: Chemical plume tracing, Brain-machine interface, Sensory feedback, Adaptive behavior, Multisensory integration, Insect brain.

1 Introduction

Recent years, along with the improvement of measurement techniques and the processing speed of CPU, the technology to control machines (such as robot arms, mobile robots and computers) using neural activities acquired from a brain (i.e. Brain-machine interface) has been developed [1-4]. Brain-machine interfaces are expected to be used for supporting injured persons and used in rehabilitation for them. In addition to these uses, brain-machine interface can be a studying method to elucidate how the motor pattern is generated in the brain. We can investigate how the brain processes sensory information in response to the dynamic change of the motor outputs of the machine by arbitrarily controlling it working as the artificial body.

In most cases, studies of the brain-machine interface have focused on generation mechanisms of plasticity in mammalian brains (such as rats, monkeys and humans). However, because the networks in the mammalian brains are highly wired, it is not so easy to extract neural signals responsible for the primary commands from mammalian brains and investigate this adaptability during executing behavioral tasks.

In this study, we solved this problem by using an insect brain which consists of comparatively small number of neurons (about 10^5-10^6 neurons) [5]. There are some studies that refer to interface between insects and robots [6], [7]. We used "a brain-machine hybrid system" [8] which is a mobile robot controlled by neural activities (Fig. 1) which are sensitive to olfactory stimuli and selective direction of visual motion and investigated compensatory response properties of motor and descending neural signals to the change of motor gain of the robot during odor source searching behavior.
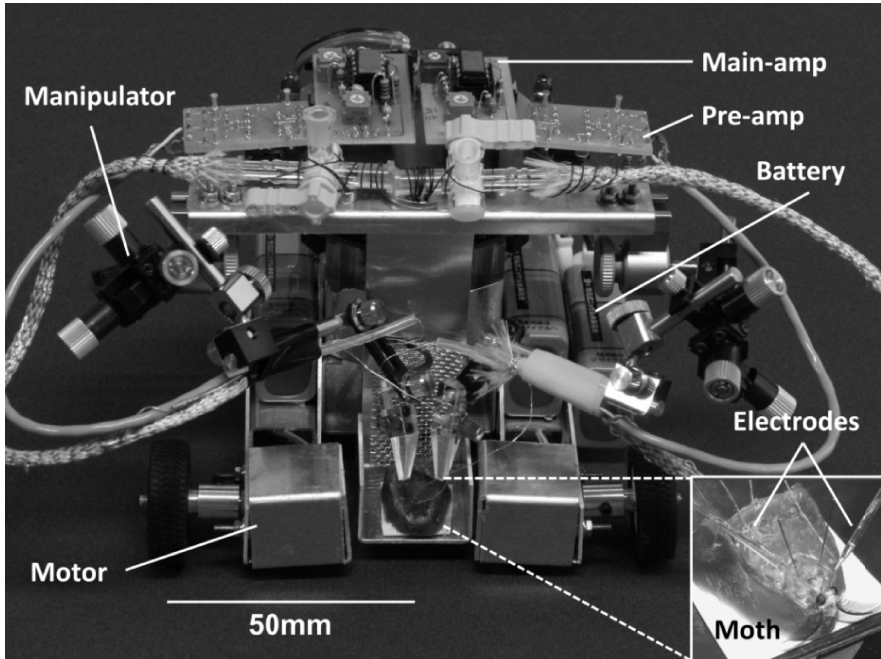
Fig. 1. Brain-Machine Hybrid System

2   Brain-Machine Hybrid System

The brain-machine hybrid system consists of two parts: a part for recording neural activities from the male silkmoth's head and a part for converting recorded signals into behavior of the mobile robot (e-puck, EPFL, Switzerland) [8].

2.1   Experimental Animal

We used a male silkworm moth (Lepidoptera: *Bombyx mori*) as an experimental animal. The reasons to select a male silkmoth are as bellow.

- Behavior of a silkmoth is only driven by female sex pheromones. Unless it doesn't detect pheromones, it doesn't move. We can also excite their olfactory neural pathways by giving pheromone stimuli.
- A silkworm moth doesn't fly. It walks to approach a female moth by repeating a set of programmed behavior (surge walking, zigzagging, loop turn) upon detecting a female sex pheromone (Fig. 2) [9-11]. This programmed behavior coincides with odor source searching behavior of other flying moths [12]. The walking trajectories can be described in two dimensional coordinate, and it is a good model animal to analyze and model behavioral strategies.
- Silkmoths have been used as model animals in biological studies (such as genetics, neuroethoogy and biochemistry) for a long time. Olfactory neural pathways in the silkmoth's brain are well studied, and activities of some neurons correlate steering motor behavior. They are candidates for command signals to control the robot [13-16].
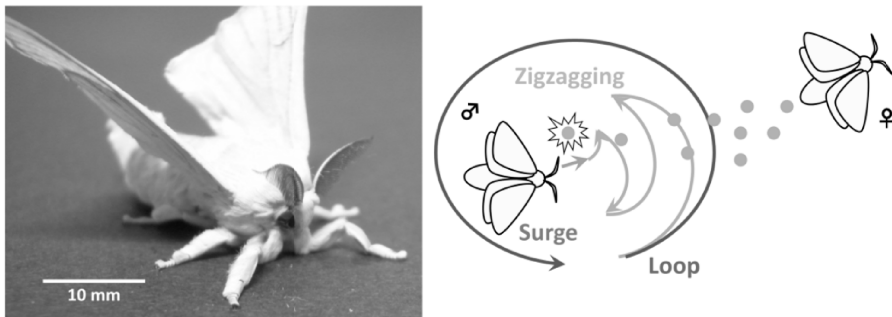

**Fig. 2.** Silkworm moth and its behavioral pattern

2.2   Recording Neural Activities

To record command signals of the silkmoths during odor source searching behavior, we focused on the activities of the 2nd cervical nerve b (2nd CNb) (Fig. 3). The 2nd CNbs are a pair of motor neurons innervating to the neck muscles swinging the moth's head. They have connections with the descending interneurons (DNs) conveying command signals from the brain to the thorax where actuators such as legs and wings are placed [15]. Because steering information during odor source searching behavior is generated in the brain and is conveyed to the thorax, it is assumed that the 2nd CNbs also convey steering information [13-15]. Based on simultaneous observations of head swing and walking during odor source searching behavior, the angular velocity of the moths' turning walk and angle of head swing were found to be in agreement [13], [17]. Moreover, the 2nd CNb is a nerve bundle consisting of only 5 motor neurons, and it is not so difficult to analyze recorded signals from the 2nd CNb by sorting the units [8].

Neural activities were recorded as previously described [13], [16]. We recorded neural signals by applying the glass micro electrodes (30-40 μm) to suck the cut end

of the left and right 2nd CNbs using syringes. In the recording setup, we set the moth ventral-side up condition for suction recording. Moths could track pheromone even if they walked hanging on the ceiling of the wind tunnel (personal observation), so there has no effect of the upside-down condition of this preparation. In this paper, we set the right and left viewed from the ventral side as right and left to the moth.

We acquired neural activities by using amplifiers that we made [8]. We designed our instrumentation amplifiers with an input resistance of 100 MΩ, a gain of 80 dB (variable), a frequency bandwidth of 150 Hz-3.2 kHz.
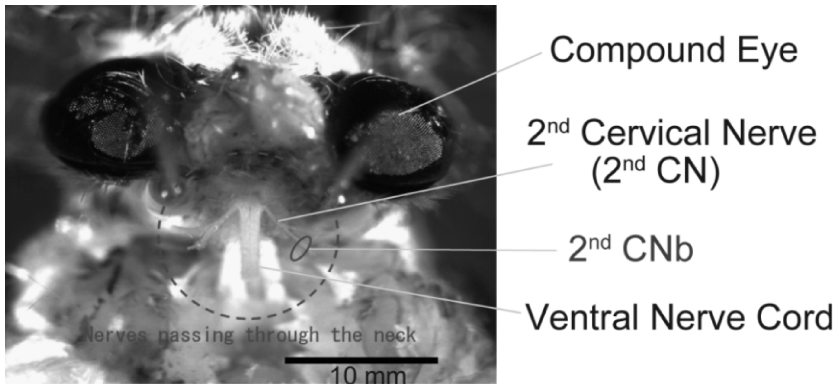
Fig. 3. Anatomy of the 2nd CNb

2.3   Setting a Spike-Behavior Conversion Rule from Visual Response Properties

In general, flying insects follow directional optical cues by rotating their body axis and rotating their heads (optomotor responses) for stabilizing their body position during flight [18-22]. Though silkmoths don't fly, they also follow the optical cues by horizontally rotating their heads. To convert the 2nd CNbs' activities into steering behavior of the robot, we investigated response properties of optomotor responses to suggested visual stimuli. As visual stimuli, we suggested the sinusoidal black and white stripe patterns 50 mm in width on a 24 inch display (GL2450HM, benQ, Japan) in front of the moth's head (distance 35 mm) and moved the pattern sidewise at a certain speed (0.25-1.5 rad/s) [23].

Spiking rate of the 2nd CNbs increased according to the angular velocity of the suggested patterns moving around the head position of the moth (Fig. 4). The 2nd CNbs exhibited excitatory responses to visual stimuli with ipsilateral direction and inhibitory responses to visual stimuli with contralateral direction comparing with the spontaneous spiking rate. These responses mean that the moth follows the direction of the optical flow by contracting its neck and turning its head in the same direction as the visual motion.

Based on the anatomical study that sidewise movement of a head is caused by complementary contraction of left and right neck muscles [13] and the correspondence of the head angle to the angular velocity of the body axis during silkmoth's walking

behavior [13], [17], we set a spike-behavior conversion rule that the angular velocity of the robot was proportional to difference of the left and right 2nd CNbs' spiking rate (Fig. 5) [8]. We also assumed the forward velocity was proportional to sum of the left and right 2nd CNbs' spiking rate. The control cycle is 0.1 s. The proportional constants were given by the angular velocities of the visual stimuli and the corresponding spiking rates.
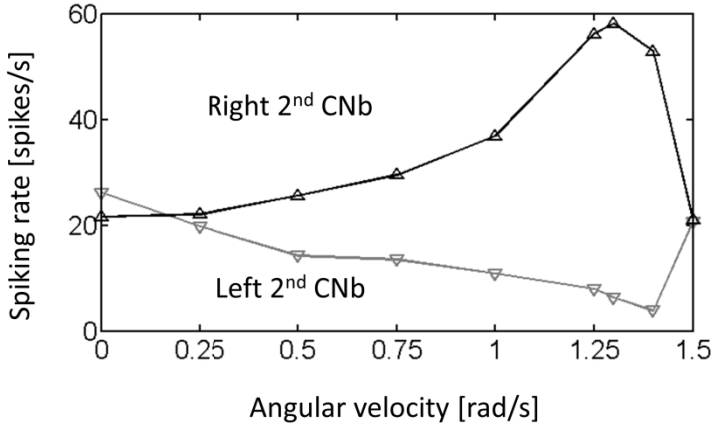

Fig. 4. Responses of the 2nd CNbs to the rightward optical flow stimuli

$$v_o \propto (n_{spikes\_right} + n_{spikes\_left})$$
$$\dot{\theta} \propto (n_{spikes\_right} - n_{spikes\_left})$$

Control cycle: 0.1 s

n_{spikes} : Spikes in 0.1 s

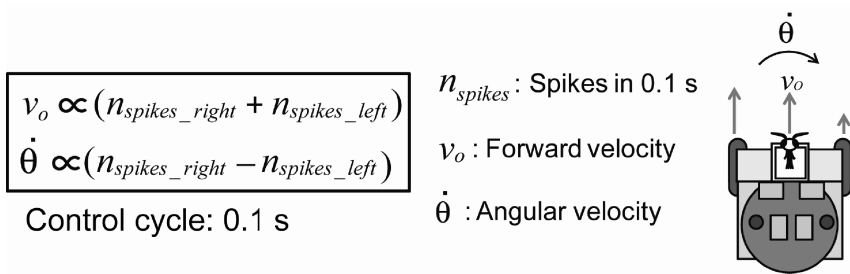v_o : Forward velocity

$\dot{\theta}$: Angular velocity

Fig. 5. Spike-behavior conversion rule

3 Disturbance Experiments Using the Hybrid System

On the brain-machine hybrid system, we can manipulate the motor outputs of the mobile robot and investigate the neural responses to the change of behavior. We introduced increments of rotational disturbances (1.0 rad/s) to the motor outputs of the robot while the robot was controlled by the neural activities acquired on the robot (Fig. 6). Disturbances have direction (clockwise and counterclockwise rotations) and different durations with 5 s intervals. We set the hybrid system at the center in a cylindrical arena. The diameter of the arena is 600 mm, while the height 526 mm. The inside wall of the arena is patterned with sinusoidal stripes to simulate a visual condition. The width of a stripe is 47.5 mm.
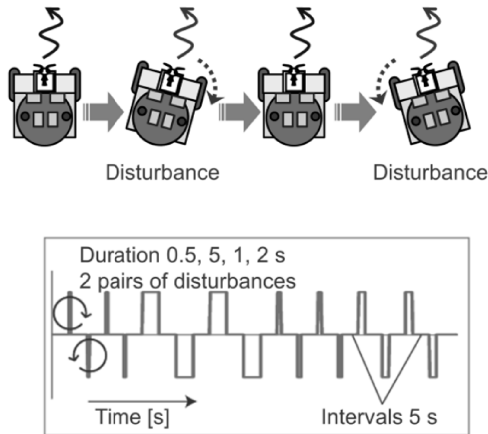
Fig. 6. Protocol of disturbance experiments

Fig. 7 shows typical neural responses to the given increments of disturbances with the direction. We calculated the angular velocity of the robot according to the conversion rule in Fig. 5. Positive and negative values of the angular velocity in Fig.6 indicate counterclockwise and clockwise rotations, respectively. The motor output of the robot was given by the sum of disturbances and neural outputs. When the negative angular velocity (clockwise rotation) disturbances were given, the neural responses exhibited the positive angular velocity to cancel out the disturbances in the motor output. Namely, the disturbances were cancelled out by the neural responses in directions opposite to the disturbances (Fig. 7). Comparing with the spontaneous spiking rate, activities of the left and right 2nd CNbs exhibited excitation during clockwise and counterclockwise rotations, respectively (Wilcoxon signed-rank test, p < 0.05, N = 8) (Fig. 8). Bar graphs in Fig.8 indicate spontaneous spiking rate of the left and right 2nd CNbs and spiking rate during clockwise and counterclockwise rotational disturbances.
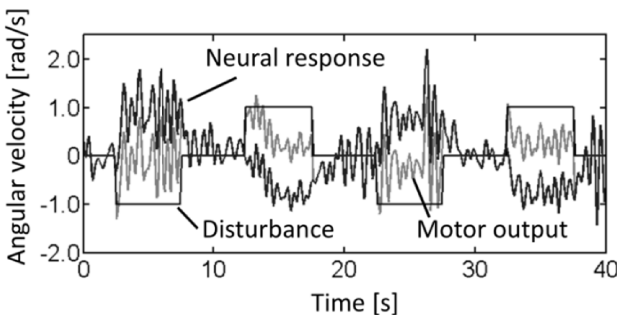
**Fig. 7.** Typical neural responses to the disturbances
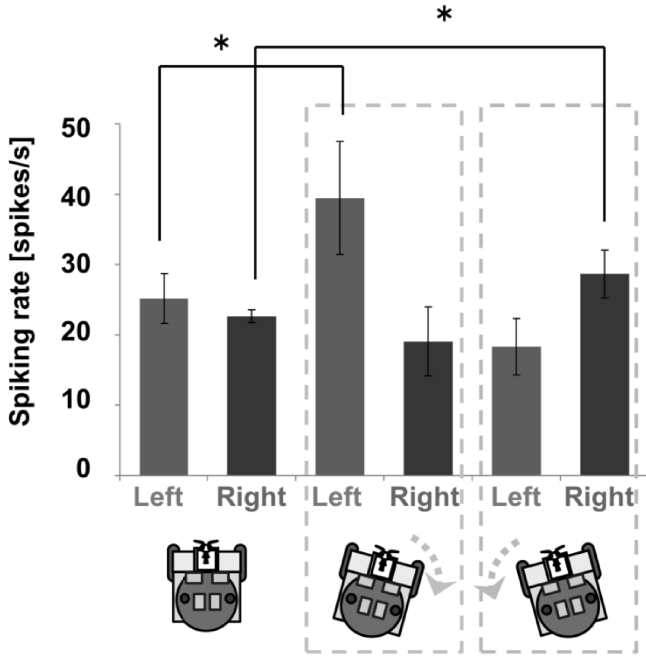
Fig. 8. The left and right 2nd CNbs' response properties to rotational disturbances (*: Wilcoxon signed-rank test, $p < 0.05$)
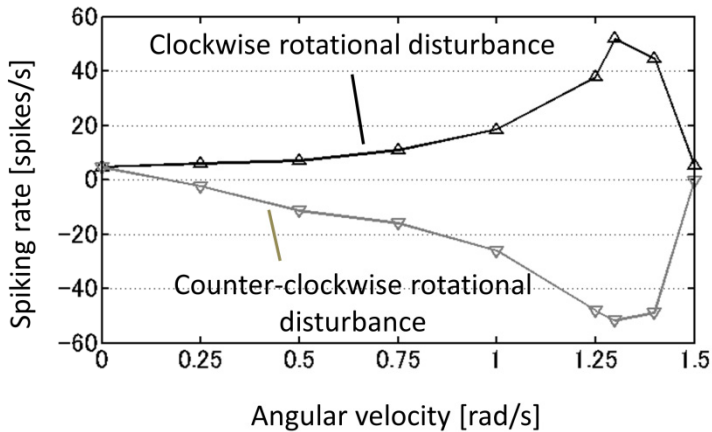
Fig. 9. Difference between the spiking rate of the left and right 2nd CNbs in response to the disturbances

Fig. 9 shows the difference of the left and right 2nd CNbs in response to the rotational disturbances. The left 2nd CNb shows excitatory responses to the clockwise rotational disturbances, and the difference of the spiking rate between the left and right 2nd CNb   becomes positive (Fig. 9). The response pattern to the disturbances in Fig. 9 corresponds to the response pattern to the optical flow stimuli shown in Fig.4. In addition, these responses to the disturbances disappeared when the compound eyes of the moth were covered with aluminum foil. These properties mean that the visual feedback works to compensate for the disturbances.

Moreover, we changed the proportional constants of the spike-behavior conversion rule into the angular velocity double and half conditions and investigated the neural responses to the disturbances as in normal condition (Fig. 6). Fig.10 shows spiking rate of the left 2nd CNbs in response to the disturbances under the different angular velocity gain conditions (normal gain: x 1, double gain: x 2, half gain: x 0.5). Comparing with the spontaneous spiking rates, the 2nd CNbs exhibited excitation under every angular velocity gain conditions in response to the disturbances (Fig. 10). However, the amount of spiking rates differed depending on the gains. Comparing with the normal gain condition, spiking rates increased in the half gain condition, and spiking rates decreased in the double gain condition (Fig. 8). Moths on the hybrid system could cancel out the disturbances even though the motor gain was altered, moths on the robot cancelled out the disturbances by increasing or decreasing the spiking rate.
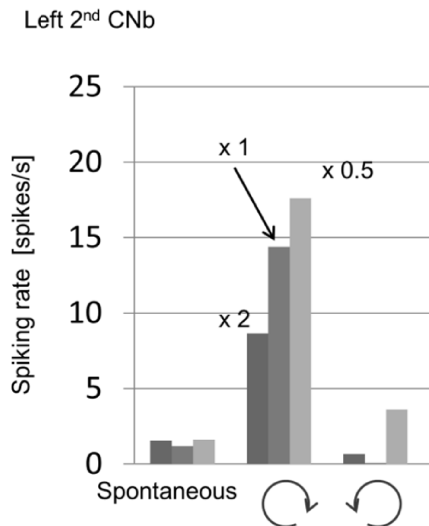

Fig. 10. Spiking rate of the 2nd CNb in response to the clockwise and counterclockwise rotational disturbances

4   Odor Source Orientation Experiments

We tested whether the compensatory responses to the disturbances (Fig. 10) were also observed in odor source searching behavior. We manipulated the proportional

constants of the spike-behavior conversion rule and switched them between the normal angular velocity gain and the double angular velocity gain every 10 s during odor source localization experiments. Orientation experiments were held in a wind tunnel with its inside wind speed 0.65 m/s, and the odor source was set at 500 mm upwind from the starting point of the hybrid system (Fig. 11) [8]. We controlled the releasing frequency of the pheromone at 2 Hz by controlling an electric valve. Odor stimuli were delivered in the conventional way used in the previous study [11]. To simulate the visual condition in the wind tunnel, we put a 300 mm square checkerboard pattern on the ceiling and 120 mm width black and white sinusoidal stripes on the inside wall of the wind tunnel. We set a video camera (HDR-XR520V, SONY, Japan) to record movement of the robot to analyze its trajectories.
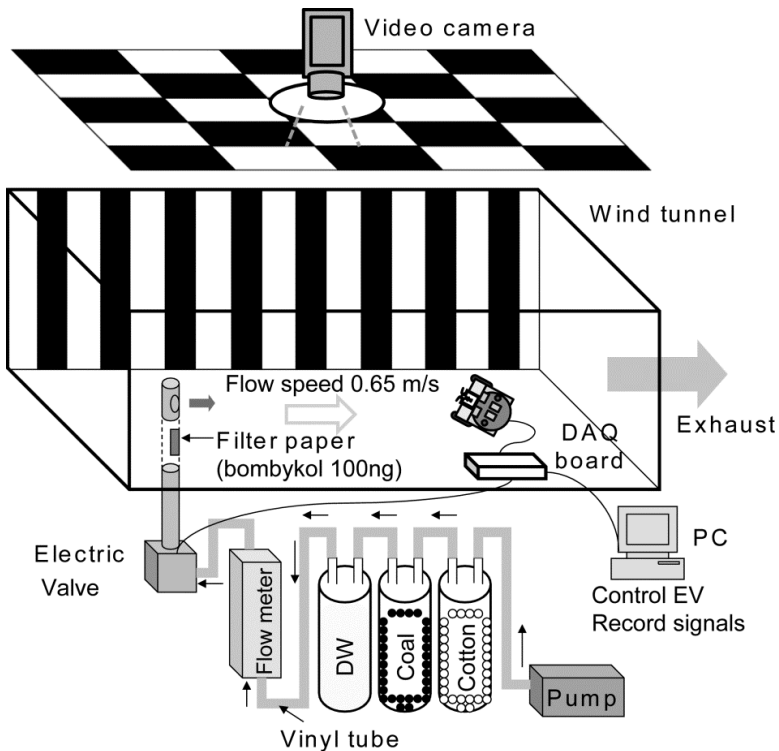

Fig. 11. Experimental setup for odor source orientation

   Moths on the hybrid system inhibited neural responses in response to the change of the motor gain and succeeded in odor source orientation (Fig. 12). In Fig. 12, the upper graph indicates neural activities of the left and right 2nd CNbs, and the lower graph indicates the histogram of the left and right 2nd CNbs. The upward histogram indicates spiking rate of the left 2nd CNb, and the downward histogram indicates the right 2nd CNb. Activities in both of the 2nd CNbs were inhibited during the angular velocity double gain orientation (Wilcoxon signed-rank test, $p < 0.05$, N = 8)
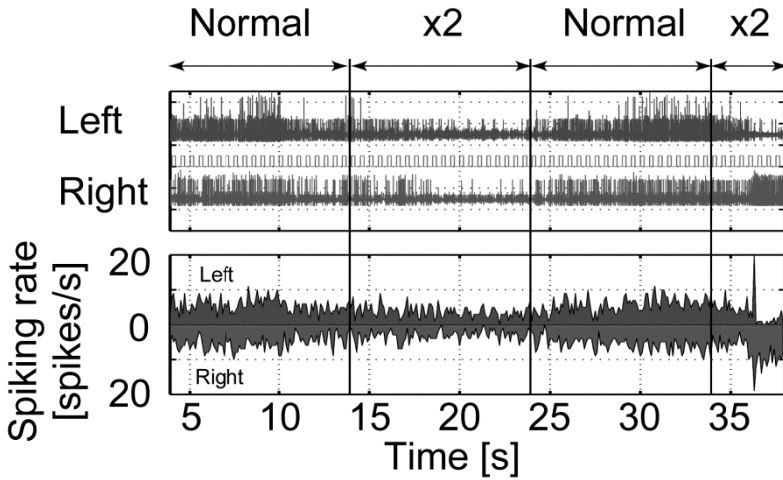
Fig. 12. Neural activities of the left and right 2nd CNbs during odor source searching behavior
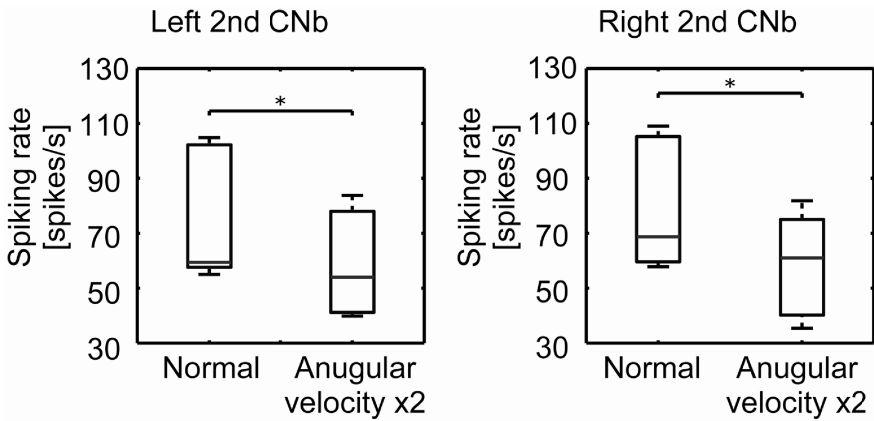
Fig. 13. Spiking rate of the left and right 2nd CNbs during the normal angular velocity conditions and the angular velocity double conditions

(Fig. 13). Average angular velocities acquired on the hybrid system during orientation experiments were 1.1 ± 0.3 rad/s (normal gain) and 1.3 ± 0.4 rad/s (double gain), and there was no significance between the two angular velocities. This means that moths can compensate motor gain of the hybrid system, and the behavior of the hybrid system is not simply decided by the spike-behavior conversion rule. Moths adjust their angular velocity to their appropriate value using the sensory feedbacks caused by their behavior.

5   Conclusion

In this study, we investigated the modification of the insect's command neural activities in response to the manipulation on the sensory feedbacks using the mobile robot controlled by the neural signals recorded from the directional selective neurons in the silkmoth cervical connective. We focused on the neck motor neurons corresponding to the deflection, lateral and sidewise translation movement in the fly's neck motor system [24]. As a result, an insect showed the ability to compensate for the given disturbances of the angular velocity, and performed compensatory responses to the changes of the motor gains even in the odor source searching behavior. This indicates that insects have the appropriate angular velocity during odor source searching behavior and compensate for the disturbances using visual feedback caused by the self-movement. In a previous work, it was also reported that moths exhibited the ability to compensate for the extraordinary behavioral conditions [25]. There are several studies that flying insects control their odor source searching behavior using optomotor responses [26-27]. However, the neural mechanisms underlying the multimodal sensory processing is poorly understood. Our experimental platform can be the effective tool to elucidate the mechanisms. In addition to the investigation of the neural mechanisms, to validate the hypothesis that the moths have appropriate angular velocity, we are now analyzing the contribution of the angular velocity to the effective odor source searching behavior in simulation experiments and experiments using the robot with gaseous sensors available in real environments.

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