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Tactile Information Processing for the Orientation Behaviour of Sand Scorpions

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1. Introduction

Arachnids including sand scorpions and spiders use their tactile sense organs, called basitarsal compound slit sensilla (BCSS), to detect their prey. The sense organs consisting of mechanoreceptors are located at or near joints in the cuticle, and they can sense a vibrational signal caused by prey movement. The nocturnal sand scorpion *Paruroctonus mesaensis* has a distinguished capability of finding their prey only with these tactile senses. The sand scorpions show their orientation behaviour of positioning themselves directly towards their prey and then run into the prey when there is a vibration disturbance caused by the prey. According to the biological researches (Brownell & Farley, 1979, Brownell, 1984), it is presumed that the sand scorpions respond to Rayleigh waves, surface waves of sand, to detect the direction of a vibration source and possibly longitudinal vibrations to estimate the distance. Especially, the time delay between arrival of a vibration signal at the BCSS sense organs is an important cue to determine the direction of their prey (Brownell & Farley, 1979).

The central nervous system should process stimulus-locked neuron firings of the sense organs on their eight legs to induce the orientation behaviour. How the nervous system is organized to handle the orientation behaviour is still an open question. Only a few studies explain this behaviour mechanism. Stuerzl et al. (2000) introduced a neuronal mechanism to support the orientation behaviour of scorpions, and it is based on the difference of the arrival time of stimulus signals produced at sense organs on their legs. They argued that the brain of sand scorpions receives sensor signals from mechanoreceptors on their eight legs and processes an inhibition mechanism among a set of command neurons projected from the sense organs on each leg. This inhibitory interaction leads to more accumulated firings of the command neurons near the prey source and less firings at the opposite sides. The accumulated neuron firings thus form a tuning curve for a specific resource direction. Then the distribution of neuron firings can vote to determine the resource direction.

In fact, arachnids have sensory projections to the central nervous system for each leg (Babu & Barth, 1989, Anton & Barth, 1993). Previously Brownell and Farley (1979) suggested that eight command neurons (or eight clusters of neurons in the brain) accumulate neuron firings from mechanoreceptors on the eight legs of scorpions, respectively and also interact each other with triad inhibitions. According to the triad inhibition hypothesis, early arrival of vibration stimulus to mechanoreceptors on a leg excites the corresponding command

Source: Sensors, Focus on Tactile, Force and Stress Sensors, Book edited by: Jose Gerardo Rocha and Senentxu Lanceros-Mendez, ISBN 978-953-7619-31-2, pp. 444, December 2008, I-Tech, Vienna, Austria

neuron and the command neuron subsequently inhibits three command neurons on the opposite side. This inhibition mechanism forms an appropriate tuning curve of neuron firings for the resource direction. Brownell and Farley (1979) built this conceptual model with triad inhibitions for interaction over the eight receptor neurons (command neurons) and later Stuezl et al., (2001) tested the hypothesis with a neuronal model. Triad inhibition mechanism over a stimulus vibration showed a good agreement with the real orientation data of sand scorpions. Recently Kim (2006b) showed that pentad and heptad inhibitions as well as triad inhibitions can determine the resource direction. Thus, we infer that inhibition processes play a critical role for the orientation behaviour.

Once the distribution of neuron firings is available for the set of receptor neurons, the accurate turning angle can be decided. Population coding (Georgopoulos et al., 1982, Pouget et al., 1998, Deneve et al., 1999) over a set of accumulated neuron firings, that is, voting calculation can determine the final turning angle towards a prey (Stuerzl et al., 2000). The voting contribution of the neuron activations from the eight directions can be simply calculated (Georgopoulos et al., 1982) as follows:

$$ze^{i\phi} = \sum_{k=1}^m z_k e^{i\phi_k} \quad (1)$$

where z_k is the firing rate or spike counts for each direction and ϕ_k is the angular position for the k -th leg direction ($m=8$). The argument ϕ will represent the direction that the scorpion finally chooses. Each directional unit is assigned the weight proportional to the activation, and a population of neurons can determine the vector direction by the voting procedure.

Triad, pentad, heptad inhibition connections among a set of command neurons can lead to a good agreement with the real orientation data of sand scorpions (Kim, 2006b). However, the effect of weight configurations and synaptic delays among the eight receptor neurons have not been studied in detail. In this paper, we investigate the role of inhibition mechanism and synaptic delays in the network configuration among the command neurons to determine the direction of a vibration source. Also we will re-visit the triad inhibition hypothesis suggested by Brownell and Farley (1979). Relevant works were presented in the paper (Kim, 2006a, 2006b).

2. Command neurons

There are eight legs for sand scorpions and their foot positions form a circle (Brownell et al., 1979), as shown in Figure 1. With this structure, we can formulate the time difference of a vibration stimulus arrival on a set of legs. The time delay of vibration between a pair of legs can be calculated simply (Stuerzl et al., 2000) as

$$\begin{aligned} \Delta t(j,k) &= \frac{1}{v} (d(p_j, \bar{s}) - d(p_k, \bar{s})) \\ &\approx \frac{R}{v} [\cos(\phi - \theta_j) - \cos(\phi - \theta_k)] \end{aligned}$$

where $\Delta t(j,k)$ is the time difference of Rayleigh waves between the j -th and k -th foot, $d(\alpha, \beta)$ is the distance between position α and β , p_k is the position of the k -th foot, \bar{s} is the position of

a vibration source, R is the radius of the foot circle (see Fig. 1, $R \cong 2.5$ cm), v is the Rayleigh wave speed in the sand ($v \cong 50$ m/sec), ϕ is the angle of vibration source, and θ_k is the angle of the k -th leg from the front direction ($\theta_k = 18, 54, 90, 140, 220, 270, 306, 342$ degree). According to the equation, the maximum time difference of stimulus on a pair of legs is around 1 msec.

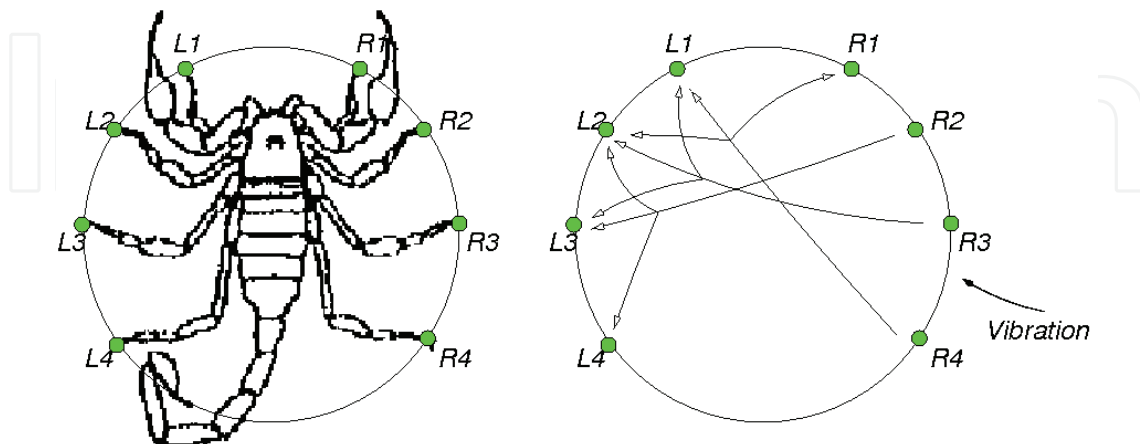


Fig. 1. Foot position of sand scorpions in a circle and triad inhibitions in the eight command neurons (reprinted from (Brownell, 1984; Brownell and Farley, 1979))

The neuron firings in the sense organs on legs depend on the amplitude of vibration signal, which is generated by prey movement. A *command neuron* or *receptor neuron* corresponding to each leg is activated by BCSS, and it accumulates the sensor activations. As shown in Fig. 1, there are eight receptor neurons in the brain and the command neuron for each leg receives inhibitory signals from three neurons on the opposite side, which is called triad inhibitions among command neurons. Stuerzl et al. (2000) assumed that the inhibitions have synaptic delay about 0.7 msec. Once sense organs on a leg first detect a vibration signal, the signal is transmitted to the corresponding command neuron. Then the inhibitory neuron signals from the command neuron often arrive at the three receptor neurons on the opposite side earlier than the vibration waves stimulate the three receptor neurons. Therefore, the neurons on the opposite side are deactivated for the vibration signals whilst the receptor neurons near the vibration source have intense neuron firings. The distribution of these accumulated neuron firings or the averaged firing rates on the eight directions will determine the orientation direction of scorpions capturing their prey. Here, the time delay from sense organs to the command neuron is common for each leg, and so what command neurons receive stimulus signals in an earlier time or later time is an important cue to determine the orientation.

For the neural mechanism, the perception vector for the orientation behaviour is a distribution of the weighted average of the sensor activations in the preferred directions, responding to a given stimulus. We can assume the stimulus direction follows population coding (Georgopoulos et al., 1982). It is represented as a sinusoidal array of eight elements for the sensor activations. The phase of each element follows the angular position of the corresponding leg (see Fig. 1).

3. Experiments

We simulate neuronal processes for the orientation behaviour. For our experiments, the command neurons in the brain receive stimulus signals at the same angular position as

sense organs of sand scorpions. We modelled the neuronal firings of the eight command neurons with inhibitory interaction by following our previous works (Kim, 2006b). Each receptor neuron has an integrate-and-fire model and the firing rate is proportional to the magnitude of membrane potential. The neural network is similar to the continuous-time recurrent neural networks (CTRNN) (Beer & Gallagher, 1992). Here, the neuron has a membrane potential f_i ,

$$\begin{aligned} \tau \frac{df_i}{dt} &= -f_i(t) + \sum_{j=1, j \neq i}^8 \mu_{ji} z_j(t - \delta) + g I_i(t) \\ z_j(t) &= H(1/\{1 + \exp[-(f_j(t) + \beta_j)]\} - 0.5) \\ H(x) &= \begin{cases} x & x > 0 \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

where τ is the time constant, z_j is the firing rate of the j -th receptor neuron for a burst of neuron spikes, δ is the synaptic delay of inhibitory connection, μ_{ji} is the weight from the j -th neuron to the i -th neuron, I_i is the intensity of the sensory input for the i -th leg, g is a gain factor, β_j is a bias term and $H(x)$ is a rectifying function to obtain positive firing rates. In the experiments, we set $\beta_j = 0$, $\tau = 0.33$, $g = 1$.

Without any interaction signal among command neurons, each neuron produces neuron firings purely depending on the stimulus amplitude. In our experiments, for each command neuron, we integrate the firing rates for 500 msec to count the number of neuron spikes for the period. The distribution of accumulated activations over the eight receptor neurons will determine the resource direction. The vibration power spectrum of sand has a peak at 300 Hz (Aicher & Tautz, 2000) and so we assume that a burst of neuron firings has 1-2 msec duration. In the test, the input signal I_i has a form of half-wave rectified sinusoid with noise, and the vibration frequency for the input sinusoid is sampled every cycle with a Gaussian distribution with mean 300 Hz and standard deviation 50 Hz. In our model, we apply 10% random noise to the input signal and the vibration power spectrum also varies around the central frequency 300 Hz. Noisy input is given into the receptor neurons and the receptor neuron activation is accumulated for 500 msec. That integration process has a low-pass filter effect on the distribution of the average firing rate or the number of spikes over the eight receptor neurons, and thus produces steady response angles with small variance to a given stimulus direction. It is reasonable to observe the distribution of neuron firings accumulated for a time interval of 500 msec, when we consider the biological test as in Brownell and Farley's experiments (Brownell & Farley, 1979)

We first tested the orientation direction of scorpions with triad inhibitions among the eight receptor neurons. For triad inhibitions shown in Fig. 1, L_k neuron has triad connections with R_{4-k} , R_{5-k} , R_{6-k} neurons, and likewise R_k with L_{4-k} , L_{5-k} , L_{6-k} neurons for $k=1, \dots, 4$ (for convenience, $R_0=L_1$, $L_0=R_1$, $R_5=L_4$, $L_5=R_4$). Inhibitions among the receptor neurons greatly influence the decision of resource direction. If we assume there is no inhibition at all, each receptor neuron will have almost the same level of neuron firings and the direction cue cannot be observed. Fig. 2 shows how the temporal difference of sensory afferents with the triad inhibitions changes the neuron firings. $L1$ neuron initially produces neuron firings for the onset of stimulus vibration and later receives an inhibitory signal from $R3$ neuron after an inhibition delay time. Accordingly, the number of spikes for the neuron $L1$ will be depressed by inhibition. The inhibition signal arrives at $L2$, $L3$ neurons earlier than the

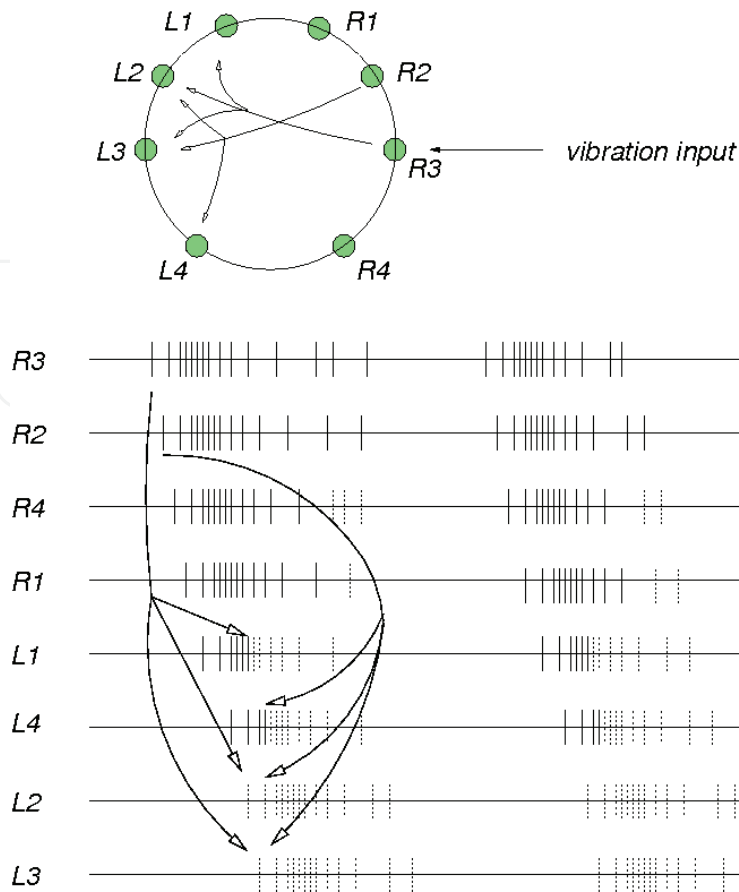


Fig. 2. Sequence of neuron firings with inhibitory actions among the eight receptor neurons (vibration source is given at the direction of 90 degree; solid spikes: actual spikes, dotted spikes: spikes inhibited by other neurons)

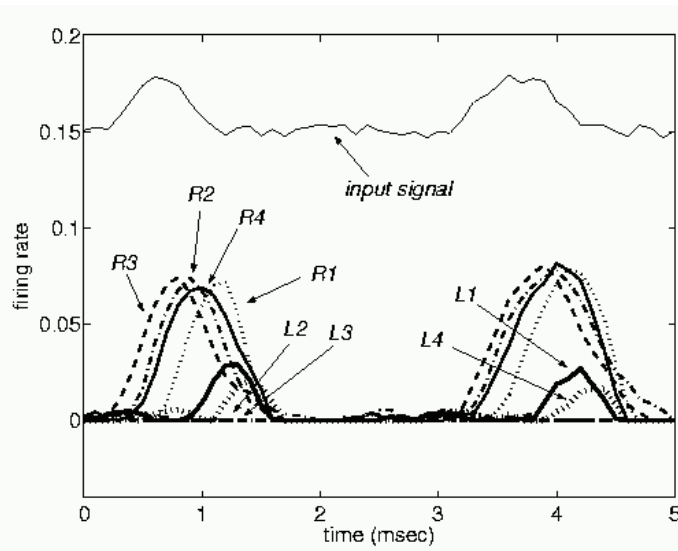


Fig. 3. Firing rate of receptor neurons, z_j with a half-wave sinusoidal input at the direction of 90 degree (L_2, L_3 neurons have almost no firing by inhibitory signals from R_2, R_3, R_4 and L_1, L_4 have relatively low amplitudes)

vibration stimulus innervates the neurons and thus no neuron firing is detected. Similar inhibition operation is found among $R2$ neuron and $L2, L3, L4$ neurons on its opposite side. Spikes at $L1, L4$ neurons will subsequently trigger another inhibition into $R3, R4, L4$ neurons and $L1, R1, R2$ neurons, respectively. In Fig. 3, we can observe the transition and distribution of firing rates in time course. We characterize the response of the receptor neurons by the total number of neuron spikes in a fixed time interval, which can be obtained by integrating the firing rates in the interval, say, for 500 msec. It reduces the effect of variance due to the noise from the external stimulus, sense organs or neurons.

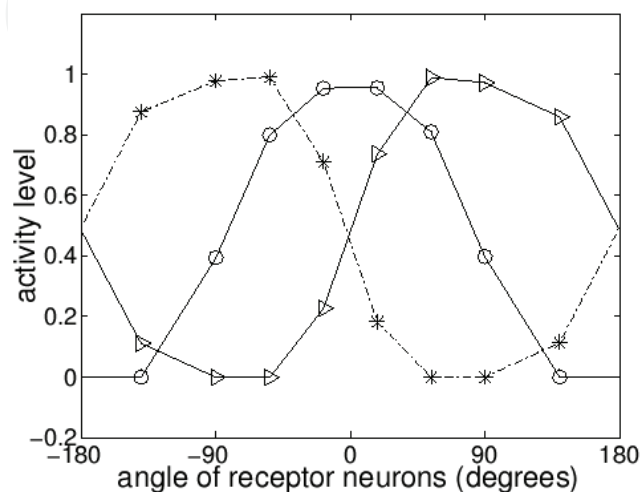


Fig. 4. Activity level of eight receptor neurons; the vibration source is given at the direction of -90 , 0 , and 90 degrees (reprinted from (Kim, 2006b))

Fig. 4 shows the activities of receptor neurons for a vibration stimulus at the direction of -90 degree, 0 degree and 90 degree, respectively. Interestingly, the activity of the eight receptor neurons roughly has a cosine tuning curve, and if it is normalized, then it follows $(1 + \cos(\phi - \theta_k))/2$, $k=1, \dots, 8$ for a given direction ϕ of vibration source. The neuron firings of the receptors are significantly influenced by the temporal difference of arrival of sensory afferent signals. It makes a relative difference of neuron firings among the eight command neurons. It shapes such a tuning curve. To estimate the resource direction from the activity curve of the eight command neurons, we need to apply a decoding method shown in equation (1). Several decoding methods are available to explain the population coding. Here, we use the complex coding, that is, simple voting mechanism with the amplitude for each phase (Georgopoulos et al., 1982, Kim, 2006b).

To find the influence of synaptic delay on the estimation of a resource direction, we tested a variety of delay time from 0.1 msec up to 1.5 msec on triad inhibitions. The vibration stimulus is given at the direction of 90 degree and the activity levels in the set of eight command neurons change depending on the transmission delays.

We first see how neuron firings fluctuate in time course. Fig. 5 shows the transition of firing rates depending on the transmission delays of inhibitions. If the delay time $\delta=0.2$ msec is taken, the duration of inhibition on the opposite side becomes small while the vibration waves continue to stimulate the neurons, as $R3, R2$ neurons cannot suppress the neuron activations of $L2, L3$ neurons sufficiently in Fig. 5(a). As a result, such interaction of the inhibition produces a distorted bimodal distribution of activity in the set of command neurons (see Fig. 6). In contrast, a long delay time, for example, $\delta=1.5$ msec allows all the

receptor neurons to be activated during the stimulus period. It thus produces a large estimation error for the resource direction.

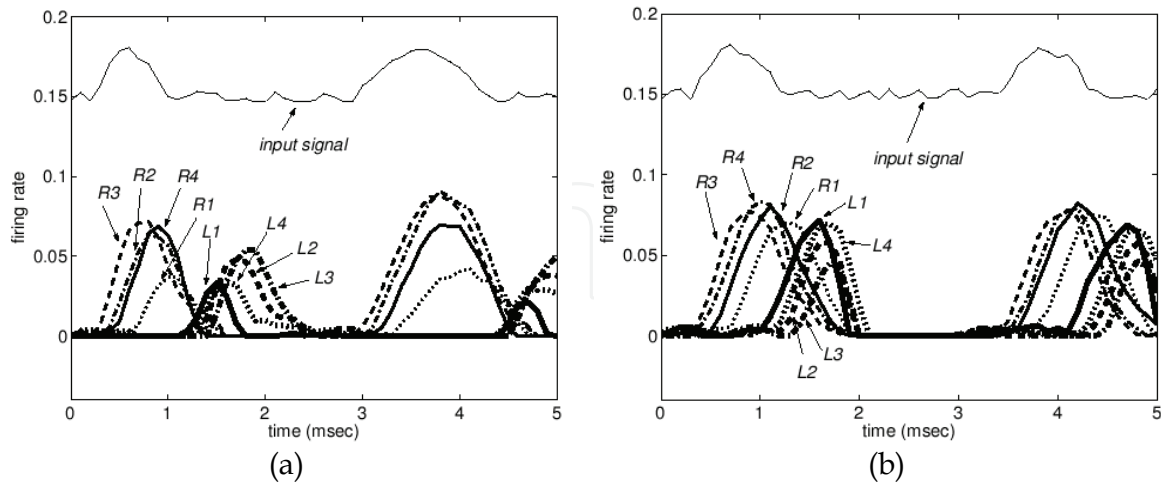


Fig. 5. Firing rate of receptor neurons with different transmission delays (a) $\delta=0.2$ msec (b) $\delta=1.2$ msec (vibration source is given at the direction of 90 degree)

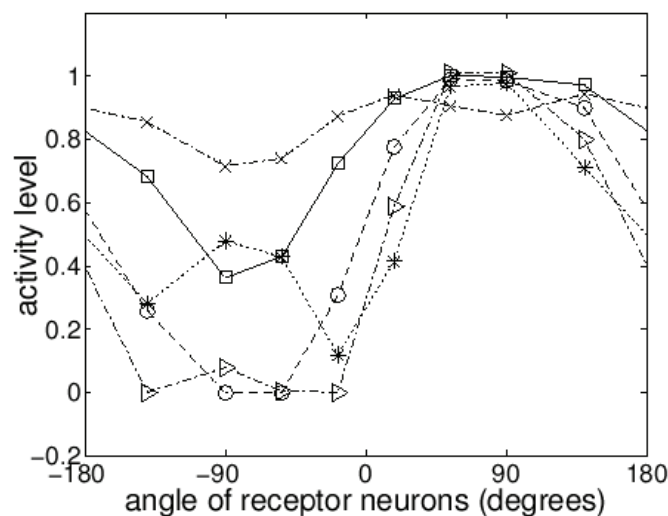


Fig. 6. Activity level of command neurons with various delays on inhibitory signals (vibration source is given at the direction of 90 degree, *: $\delta=0.2$ msec, triangle: $\delta=0.5$ msec, o: $\delta=0.8$ msec, square: $\delta=1.2$ msec, x: $\delta=1.5$ msec) (reprinted from (Kim, 2006b))

As shown in Fig. 6, especially a small delay time, for instance, $\delta=0.2$ msec will produce a small hill in the tuning curve in addition to the main cosine-like curve. It results from neuron firings which was not inhibited enough on the opposite side. That is, too small delays may not inhibit incoming neuron firings transmitted from sense organs on the opposite side. As a result, it produces a distorted bimodal-like tuning curve for the activity of receptor neurons rather than a cosine-tuning curve. However, too large delays induce a relatively small contrast among the sensory activations, since the inhibition process does not reduce neuron firings of other command neurons sufficiently - see Fig. 5(b). The decoding method in equation (1), irrespective of the distribution of neuron firings, will pinpoint an orientation angle.

Brownell and Farley (1979) showed biological experiments for the orientation of sand scorpions towards their prey. They collected the orientation data of the scorpion for stimulus vibrations at various angles. We tested our orientation simulation over the real data with a neural model described above. Here, the orientation response angles were estimated over distribution of accumulated neuron firings. Initially, we simulated a variety of transmission delays on triad inhibitions, and compared the orientation results with the real orientation data of scorpions to see how much our model matches the real data. The agreement with the real data was reasonably good within the range of 0.5 - 1.1 msec; the performances were not significantly different within that range. However, too small or too large delays show a deviation from desirable estimation of orientation angle (Kim, 2006b). Brownell and Farley (1979) tested another experiment with ablated slit sensilla on one or a few legs. From the result, they suggested a hypothesis of triad inhibitions among the eight receptor neurons. Stuerzl et al. (2000) used a stochastic model of neuron firings with triad inhibitions to examine the hypothesis, and found its good agreement with the real orientation data of scorpions. In their experiments, monad inhibitions were worse than triad inhibitions in agreement with the real data. However, how many inhibitions are available is still unknown. Thus, we explored monad, dyad, triad, pentad, heptad inhibitions among the eight receptor neurons in the previous work (Kim, 2006b) - see the inhibition arrangements in Fig. 7.

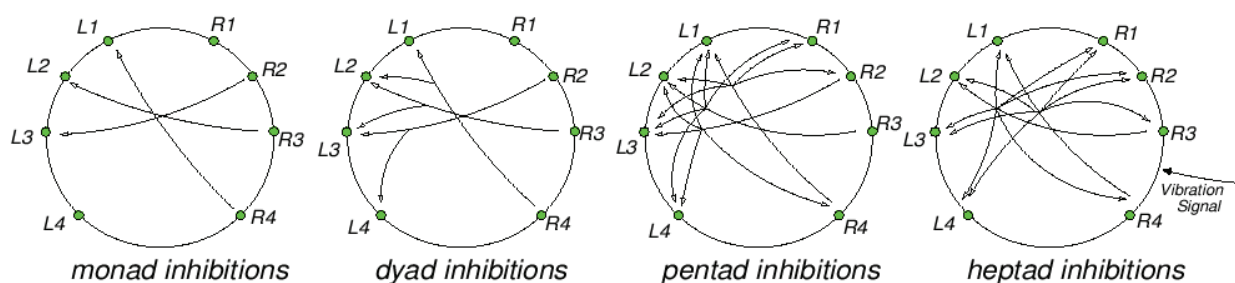


Fig. 7. Inhibitory connections among the receptor neurons (reprinted from (Kim, 2006b))

The inhibitory mechanism was tested on the biological data (Brownell & Farley, 1979, Brownell, 1984) with some slit sensilla ablated. For these experiments, we used $\delta=0.9$ msec for a delay time of inhibitory signal, which was a good delay parameter for the triad inhibition test in the above. For the monad inhibition arrangement, each receptor neuron has an inhibitory connection with a single receptor neuron on the opposite side (L_k with R_{5-k} for $k=1, \dots, 4$ and vice versa), and for the heptad connection if one neuron is activated, its inhibitory signal is transmitted into all the other seven neurons. For dyad inhibitions, L_k neuron has an inhibitory connection to two neurons R_{5-k} and R_{6-k} , on its opposite side, and similarly R_k neuron to two neurons L_{5-k} and L_{6-k} . For pentad inhibitions, each neuron transmits inhibitory signals to five command neurons except its two neighbour neurons.

Fig. 8 shows that the neural network can determine the appropriate orientation. As Stuerzl et al. (2000) showed, triad inhibitions generally produce good performance in agreement test with the real data, but monad inhibitions have poor agreement with the real data, as shown in Fig. 8(b) and 8(d). Three inhibitions or more from one neuron cell can produce good agreement. Pentad or heptad inhibitions show the best agreement in some cases (Kim, 2006b), and possibly more inhibitions rather than three inhibitions might be a plausible idea to support the orientation data. However, pentad or heptad inhibitions need more connections among the receptor neurons just for a slight improvement of the agreement.

Thus, it may be arguable that the experiments still support the triad inhibition hypothesis over the eight receptors, since their performance differences are not much significant.

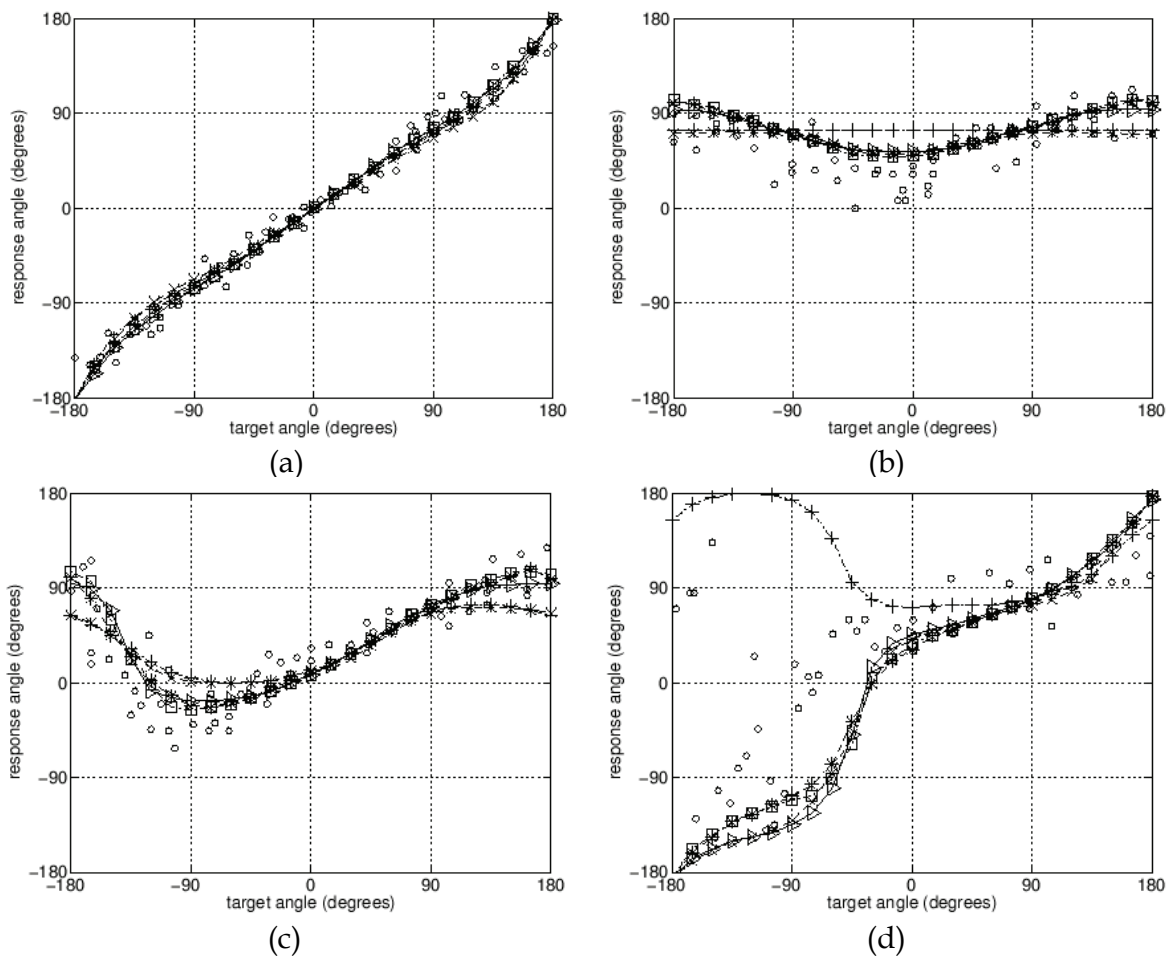


Fig. 8. Test of orientation angles with the real orientation data (a) no ablation (b) L1, L2, L3 and L4 ablated (c) L3 and L4 ablated (d) L1 and L2 ablated (o: real data, +: monad inhibition, x: dyad, triangle: triad, square: pentad, *: heptad); real orientation data of scorpions have been reprinted from the paper (Brownell & Farley, 1979, Brownell, 1984, and Kim, 2006b)

In our experiments, synaptic delays on triad inhibitions significantly influence the estimation of a resource direction. We applied a varying delay time ranging from 0.1 msec up to 1.5 msec to several arrangements of inhibitions, that is, monad, dyad, triad, pentad and heptad connections, and the results were compared with the orientation data of sand scorpions. We measured the estimation error for each sample in the orientation data and calculated the root mean squared error for each set of data. Fig. 8 shows that each arrangement of inhibition needs a little different range of delay time for good performance in the agreement test. The delay time from 0.5 msec to 1.1 msec covers the best performance in Fig. 9(a)-(c), and 1.0-1.4 msec in Fig. 9(d). It seems that triad, pentad or heptad connections produce better performance than the other connection types. From the result, we also infer that sand scorpions need a synaptic delay on the inhibitions within the range of 0.5 - 1.2 msec.

According to the agreement test, we see there is still an error between the theoretical model and the real data. The estimation error is often found in the experiments with ablated sense organs. As shown in Fig. 8(b) and 8(d), even for varying inhibition arrangements, the orientation estimation does not perfectly match the real data. We guess several factors to cause

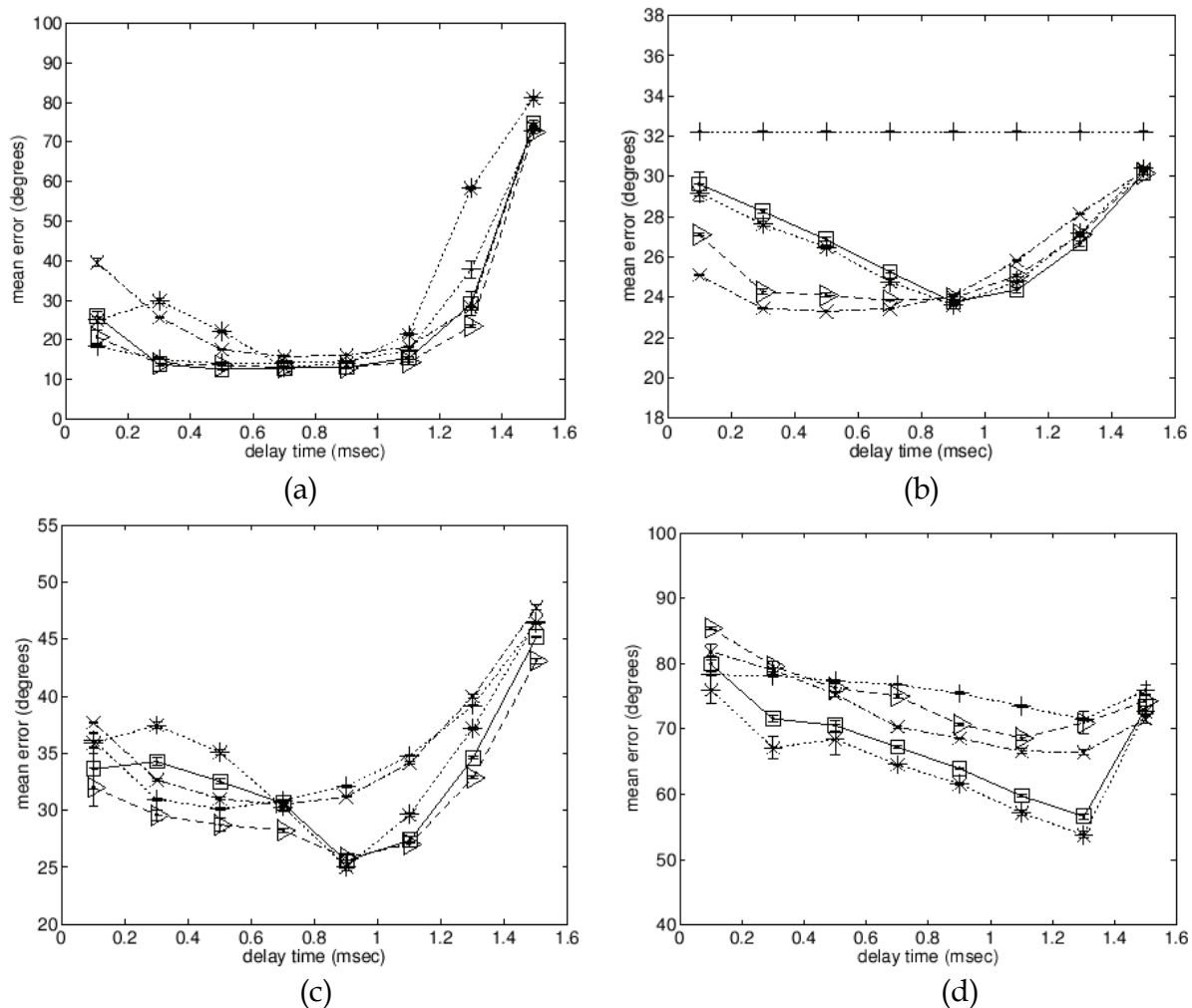


Fig. 9. Estimation error with varying delay time on inhibitory signal (a) no ablation (b) L1, L2, L3 and L4 ablated (c) L3 and L4 ablated (d) L1 and L2 ablated (root mean squared error and standard deviation is measured with 5 trials, o: real data, +: monad inhibition, x: dyad, triangle: triad, square: pentad, *: heptad) (reprinted from (Kim, 2006a))

this mismatch. Possibly sand scorpions may have different activity patterns for the receptor neurons or use a little different decoding method for the orientation. We assumed unbiased sensitivity over the eight receptor neurons for the incoming vibration waves, but it may not be true in reality. Above all, from the agreement test, receptors corresponding to front legs seem to have more contribution in the voting procedure than the others, because a large discrepancy between the estimation and the reality is observed near the front direction when the sense organs at a front leg are ablated. Or, there might exist conditional operations or neuromodulations among the receptor activations; for instance, one receptor's firings may change the contribution rate or presynaptic weights of another receptor neuron. Alternatively, different arrangement of inhibitory connections, or partly excitatory connections may be available among the command neurons. Presumably, the command neurons for the front legs may interact each other with strong inhibitions, since ablation of the sense organs on the front leg at one side seems to trigger more neuron firings of the front leg at the other side (left or right). We need further study to explain it more precisely. In fact, there are many factors to influence the agreement performance, such as synaptic delay, neuron firing rate, coupling

strengths among the receptor neurons, and decoding methods. More rigorous parameter setting and anatomical / neurophysiological result will be required for close agreement with the real data.

4. Discussion

In this paper, we have shown a simplified neuronal model to explain the orientation mechanism of sand scorpions, which is rather similar to the CTRNN network. Stuerzl et al. (2000) tested another type of neural networks, a population of spiking neurons to see how the arrival time of vibration on each leg influences the neural firings. They found the neuron firings on each leg is a function of the time difference of vibration stimulus among the triad inhibitory interactions. Our neural model is simplified to eight neurons each of which has its own firing rate to approximate the number of neuron spikes. The experimental result shows our neuron model is well fit to the real orientation data, which suggests that the eight neuron model may be sufficient to explain the orientation mechanism of sand scorpions. This simplified model has more potential for robotic application or other vibration sensing application, since it can be easily built with artificial devices.

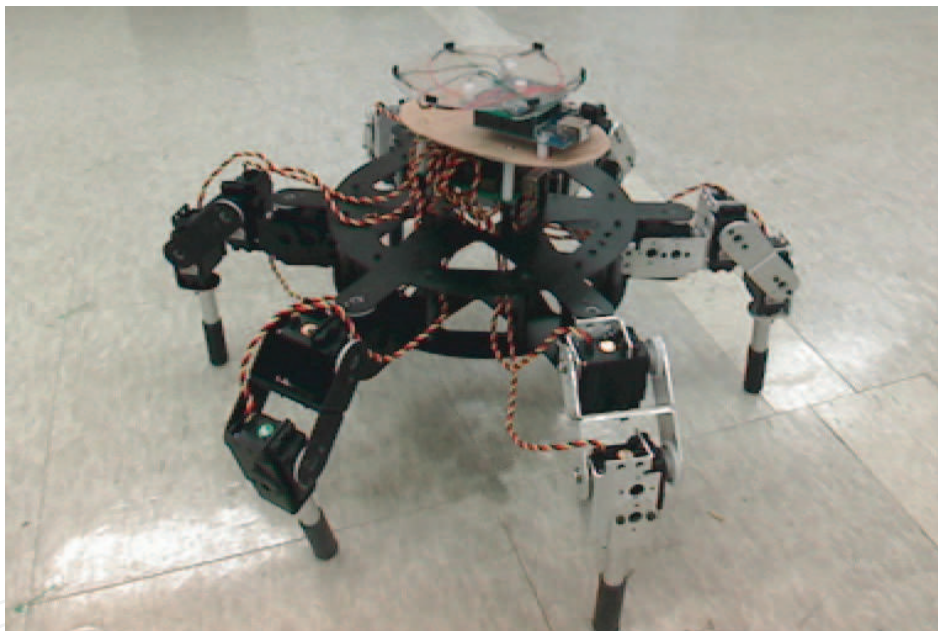


Fig. 10. Mobile robot with multi-legs

Following the suggested neural architecture, we are testing robotic orientation with tactile senses. The sand scorpions use BCSS organs near joints to detect any vibration in the environment. We mount vibration sensors, piezoelectric sensors at the foot and measure the temporal signals of vibrations. We found that the time delay between arrival of a vibration signal on robotic legs is not much significant in an office environment when a vibration disturbance is given near the robot. Rayleigh waves of vibration can be easily recognized in the desert environment for sand scorpions (Brownell, 1984), but the flat surface shown in Fig. 10 is only involved with longitudinal waves, that is, sound waves. The sound speed of the solid surface is much higher than the sound wave in the air. To apply our neural approach to the robotic system in the office environment, we need to measure high resolution of temporal signal to detect the time delay of arrival. As an alternative approach,

we can use the amplitude or power spectrum of the vibration signal. We observe that more distant area has more attenuation in the amplitude of sound waves. However, it is questionable if the distribution of amplitude attenuation can exactly pinpoint the direction of vibration source. The orientation with the two types of vibration signals will be tested in the environment similar to the desert. It is still an open question that sand scorpions use both Rayleigh waves and longitudinal waves or either for resource localization. We need further study to find the principle of orientation of sand scorpions and apply it to engineering problems.

The connectivity pattern and the time delay of inhibitory signal have been investigated in this paper. The results are based on our neural model and it seems that the neuron firings on each leg follow an almost linear function of the time difference of vibration stimulus when triad, pentad or heptad connections are used. It implies that our model is a good approximation of the realistic neuron model suggested by Stuerzl et al. (2000). To validate our neuron model, we still need further study of whether more realistic neuronal model produces the same results about the inhibitory pattern or delay.

We suggested neural networks with inhibition mechanism or suitable delay time for the inhibitory connections. However, there is no neurophysiological or anatomical evidence for the neural network of command neurons. From the experiments, it seems that the inhibitory interaction has a significant role on the localization of a prey source at least in the agreement test with the real data. We still need anatomical data on the scorpion brain to support the argument. Also if the information of the recording time of vibration signals for the sand scorpions can be obtained, it may provide the relevance and significance of the integration in our neural network.

To model the decoding process of orientation angle over distribution of neuron firings in the command neurons, we can build a neuronal layer with a lot of directional cells (Kim, 2006b). One hypothesis is that there exist a large number of direction cells to pinpoint the exact direction of the prey source and the direction is determined before the appropriate motor action. As an alternative decoding mechanism, we can build a relatively small number of neurons directly coupled to motor neurons for the orientation behaviour. With that neural structure, appropriate weights may guide the orientation angle accurately.

5. Conclusion

In this paper, we present a neuronal model to process tactile information from the sense organs of sand scorpions. We tried to explain how sand scorpions orient towards their prey when there is any vibration disturbance caused by prey. They have eight clusters of neurons in the brain to process stimulus-locked neuron firings of the sense organs on their eight legs (Anton & Barth, 1993, Babu & Barth, 1989). It is modelled simply as eight command neurons with inhibitory interactions in our neural system.

Our continuous-time recurrent neural networks can encode the temporal difference of tactile vibration on each leg, and also implement inhibitory interactions depending on synaptic delays. Then we compared the neuronal simulation results with the orientation of sand scorpions. According to the agreement test, the eight command neurons show the best performances with triad, pentad or heptad inhibitions, which implies three inhibitory connections or more may be available in the brain system of sand scorpions. Varying

synaptic delays also influence the agreement performances. The experiments suggest that they have a synaptic delay of inhibition within the range of 0.5 - 1.2 msec.

The neural model and its experiments showed that a relatively small number of neurons can achieve the orientation mechanism for a vibration source. This study can provide a foundation of tactile information processing to localize a prey source, or to detect the environmental cue with a collection of sensor signals. We still need further study to understand the orientation of sand scorpions. This will be involved with testing various factors including the coupling strength, non-uniform synaptic delays or varying neural connections among the command neurons.

6. Acknowledgements

The work has been supported by the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the IITA (Institute for Information Technology Advancement)" (IITA-2008-C1090-0803-0006)

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Sensors: Focus on Tactile Force and Stress Sensors

Edited by Jose Gerardo Rocha and Senentxu Lanceros-Mendez

ISBN 978-953-7619-31-2

Hard cover, 444 pages

Publisher InTech

Published online 01, December, 2008

Published in print edition December, 2008

This book describes some devices that are commonly identified as tactile or force sensors. This is achieved with different degrees of detail, in a unique and actual resource, through the description of different approaches to this type of sensors. Understanding the design and the working principles of the sensors described here requires a multidisciplinary background of electrical engineering, mechanical engineering, physics, biology, etc. An attempt has been made to place side by side the most pertinent information in order to reach a more productive reading not only for professionals dedicated to the design of tactile sensors, but also for all other sensor users, as for example, in the field of robotics. The latest technologies presented in this book are more focused on information readout and processing: as new materials, micro and sub-micro sensors are available, wireless transmission and processing of the sensorial information, as well as some innovative methodologies for obtaining and interpreting tactile information are also strongly evolving.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

DaeEun Kim (2008). Tactile Information Processing for the Orientation Behaviour of Sand Scorpions, Sensors: Focus on Tactile Force and Stress Sensors, Jose Gerardo Rocha and Senentxu Lanceros-Mendez (Ed.), ISBN: 978-953-7619-31-2, InTech, Available from: http://www.intechopen.com/books/sensors-focus-on-tactile-force-and-stress-sensors/tactile_information_processing_for_the_orientation_behaviour_of_sand_scorpions

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