Spatial learning correlates with decreased hippocampal activity in the goal-directed behavior of pigeons

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Abstract— **Studies have suggested that the hippocampus (Hp) plays an important role in spatial learning and avian Hp is thought to have similar functions with mammals. However, the dynamic neural pattern of hippocampal activity is still unclear in the continuous spatial learning processes of birds. In this study, we recorded the behavioral data and local field potential (LFP) activity from Hp of pigeons performing goal-directed behavior. Then the spectral properties and time-frequency properties of the LFPs are analyzed, comparing with the behavioral changes during spatial learning. The results indicated that the power of the LFP signal in the gamma band shown decreasing trend during spatial learning. Time-frequency analysis results shown that the hippocampal gamma activity was weakened along with the learning process. The results indicate that spatial learning correlated with the decreased gamma activity in Hp and hippocampal neural patterns of pigeons were modulated by goal-directed behavior.**

I. INTRODUCTION

Goal-directed behavior is to gain incentive value through reward, which is different from habitual behavior due to its thoughtful and informed nature [1]. And goal-directed behavior is vital to the survival of animals in nature because most of their behaviors such as foraging, migration, and so on, are goal-directed [2]. During executing goal-directed behaviors, the ability of spatial learning is particularly important because animals need to be familiar with the surrounding environment through exploring constantly as soon as possible. In addition, spatial learning is task-dependent, and goal-directed behavior gives it a reliable active advantage, which interacts with each other [3]. The previous studies have indicated that the hippocampal (Hp) plays an important role in spatial learning [4]. Hippocampal neurons are highly adaptive to process and encode spatial-related information to support spatial goal-directed behaviors [5][6]. Herold et al. have revealed that the avian Hp is functionally homologous to mammals [7][8]. Furthermore, Kahn and Bingman have shown that the avian Hp formation is critical not only for learning the spatial properties of goal locations but also for learning what happens at goal locations in an animal's environment [9]. Most of the studies have focused on the role of Hp on spatial learning, and some progress has been made. However, the dynamics of avian hippocampal neural activity pattern in the whole process of spatial learning is still unclear.

Therefore, the purpose of this paper is to study the dynamic changes of the behavior performance and Hp activity patterns in the process of spatial learning of the pigeons. We designed a goal-directed behavioral experimental paradigm and trained the pigeons to perform the spatial learning task in a maze. The local field potential (LFP) signals [10] in Hp were recorded when the pigeons perform the spatial learning task. Power spectral and time-frequency properties of the LFPs were analyzed to reveal the dynamic changes of neural patterns in Hp of pigeons during spatial learning. The results suggested that the hippocampal neural patterns of gamma LFPs of pigeons were modulated by spatial goal-directed behavior.

II. MATERIALS AND METHODS

A. Subject and Surgery

The experimental subjects are four adult pigeons (*Columba livia*) weighing between 450-550g (numbered by P100, P106, P110, P130). All experiments are conducted in accordance with the Animal Law of 2006 (China) and passed the review of the Life Science Ethics Review Committee of Zhengzhou University, following the regulations of the Animal Management and use Committee.

Electrode implantations of pigeons were performed when the animals were under general anesthesia. Pigeons were treated with general anesthesia (pelltobarbitalum natricum at 3% concentration, injection dose of 0.12 ml/100 g body weight) [11]. When the pigeon entered the coma state, it was fixed to the brain stereotaxic instrument. The multi-channel microelectrode array (4 × 4, Hong Kong Plexon Inc., Hong Kong, China) was implanted into the left Hp region of pigeons (A 4.5 mm; L 1.0 mm; D 1.0-2.0 mm, see Fig. 1a), according to the atlas by Karten and Hodos [12]. After the electrode implantation was completed, the pigeon would be given a recovery period of about a week.

B. Behavioral Apparatus and Experimental Paradigm

The goal-directed task of pigeon was carried out in a maze shaped like a Chinese character "田" (see Fig. 1b). The maze contains a starting point and two goal points, and there are food rewards at these points. The process of pigeons learning a path will be seen as a session, in which pigeons are more and more familiar with the certain path. When a pigeon performs the goal-directed task in one session, the food hamper in the designated goal points will be opened, and the pigeon will start from the starting point to this above goal point to get food reward. One of these processes is seen as a trial.

A session may contain several learning stages, and there will be a series of trials in each stage. Normally, after a period of spatial learning, the path learning of the pigeon from the starting point to the goal point will tend to be stable. Each
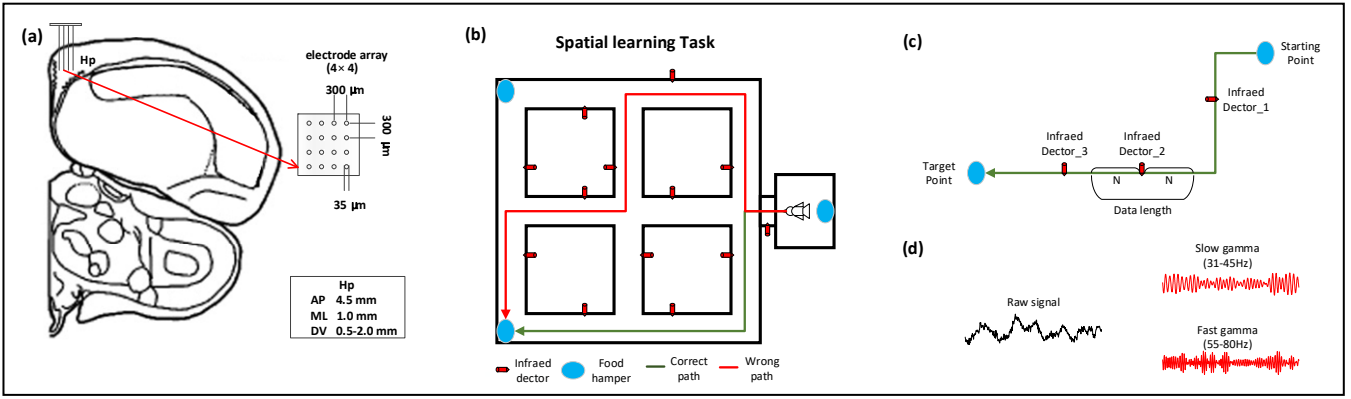
Fig. 1. Illustration of avian Hp, behavioral apparatus and data. (a) A microelectrode array was implanted in the avian Hp which marked in the figure. (b) The trail takes the green path in the figure is the correct trial, while takes the red path is the wrong trial. (c) The neighborhood data of the path center point are selected for analysis. (d) Examples of LFP traces recorded from Hp, filtered at slow gamma and fast gamma frequency bands.

pigeon has its own preferred stable "path". The correct trial is that the pigeon takes the preferred stable "path" to complete the trial (see Fig. 1b). One of these processes is seen as a trial.

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C. Data Acquisition

The signal acquisition device used in this experiment is a Cerebus^{TM} multi-channel signal acquisition system (Blackrock Microsystems Inc., Salt Lake City, USA) with a sampling frequency of 2 kHz. The above signal acquisition system can simultaneously record the neural signals in Hp as the pigeon performs the goal-directed spatial learning task. When the pigeon passes through the infrared detection devices, the marking time and position will be recorded.

Because the neural signal of the pigeon is weak and easily disturbed, the signal amplified by signal amplifier $(4000\times)$ amplification contains noises, which need to be preprocessed. A Butterworth low pass filter (0-0.25 kHz) was used to obtain LFP signal. Because different pigeons have different behavioral performances, the length of LFP signals used for analysis is slightly different. The specific processing is as follows. During the goal-directed task, the pigeon passes through three infrared devices for each correct trial. Taking the time point corresponding to the intermediate infrared device as the center point, the data can be intercepted forward and backward at the shortest time interval, and the data length in all the trials of all stages of a pigeon should be consistent (see Fig. 1c).

D. Data Processing and Analysis

Behavioral data analysis: In the whole process of spatial learning, pigeons go through the process from "unable" to "able". Simply speaking, the path from the starting point to the goal point seems to be multivariate and complex for the pigeons in the early stage. After a period of learning, the pigeons will find the preferred path and steadily follow this path. The whole continuous spatial learning process was divided into four stages according to the degree of learning in

this study. There are two main behavioral indicators for measuring the pigeon's performance to be calculated. One is the average time-consuming of all "correct trials" in each stage, recorded as $t(i)$ $(i = 1,2,3,4)$. The other is behavioral accuracy in each stage, recorded as $a(i)$ $(i = 1,2,3,4)$. The two indicators are calculated by the following formula,

$$t(i) = \frac{tr(1) + \cdots + tr(j) + \cdots + tr(n)}{n}, 1 \le j \le n \quad (1)$$

$$a(i) = \frac{n\_correct}{n} \times 100\% \quad (2)$$

where, $tr(j)$ is the time consumption of the jth correct trial. n is the total number of trials in one stage. $n\_correct$ is the number of correct trials in the corresponding stage.

Power spectral analysis: The power spectral analysis is used to observe LFP properties in the time domain during spatial learning. This method reveals the relationship between the frequency and power of the LFP signal. The multi-tapper method [13] was used to estimate the power spectral of LFP in this paper. Specifically, given an LFP signal $x(t)$, the LFP-power is calculated by the following formula,

$$P = \frac{1}{N}\left[\sum_{t=0}^{N} x(t)^2\right]^{\frac{1}{2}} \quad (3)$$

where N is the length of $x(t)$.

Time-frequency analysis: Time-frequency analysis converts the LFP signals from the time domain to the frequency domain. This method shows the relationship between the frequency and time of the LFP signal. Wavelet transform [14] was used here,

$$WT(\alpha, \tau) = \frac{1}{\sqrt{\alpha}} \int_{-\infty}^{\infty} x(t) \times \psi\left(\frac{t - \tau}{\alpha}\right) dt \quad (4)$$

where, α is a scale variable, which determines the time accuracy and frequency accuracy. τ is the translation variable.

The energy of LFP signals can be calculated by wavelet transform. In order to show the energy change of the signals more intuitively, the energy ratio of each stage is calculated here,

$$ER = \frac{e(i)}{e(1)}, 1 \le i \le 4 \quad (5)$$

where, $e(i)$ is the sum of energy in the ith stage.

III. RESULTS

A. Behavioral Performance

Fig. 2 depicts the change of behavioral performance of four pigeons in the whole spatial learning process.
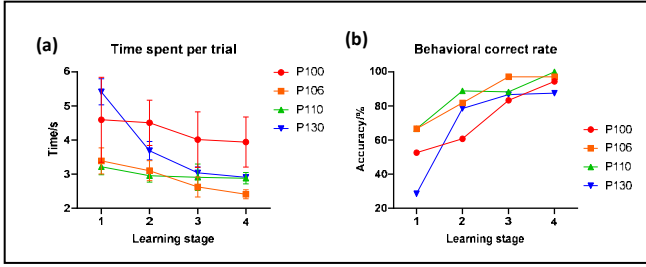

Fig. 2. Behavioral performance. (a) Time spent per trial. (b) Behavioral correct rate.

Fig. 2a shows the curve of the average time spent by four pigeons completing the correct trial along with the learning stage. In the first stage, all the pigeons spent more time to arrive at the goal and the behavior accuracy is not satisfactory. But in the last stage, the time pigeons spent per trial decrease gradually along with the promotion of the learning process, and the accuracy has improved (see Fig. 2b). In brief, with the deepening of the spatial learning process, the average time consumption shows a downward trend, while the behavior accuracy shows an upward trend. These results show that pigeons can accomplish goal-directed tasks more skillfully through spatial learning.

B. LFP Power Spectral Properties

In this paper we analyzed the power spectral properties of LFP signals in the gamma band. To avoid the bad results caused by power frequency interference, we divide the gamma band into slow gamma (30-45Hz) and fast gamma (55-80Hz), simply written as $S\gamma$ and $F\gamma$ [15]. Spectral analysis on these two sub-bands was carried out, and the results are shown in Fig. 3a. The power spectrum curves of the LFP signals of four
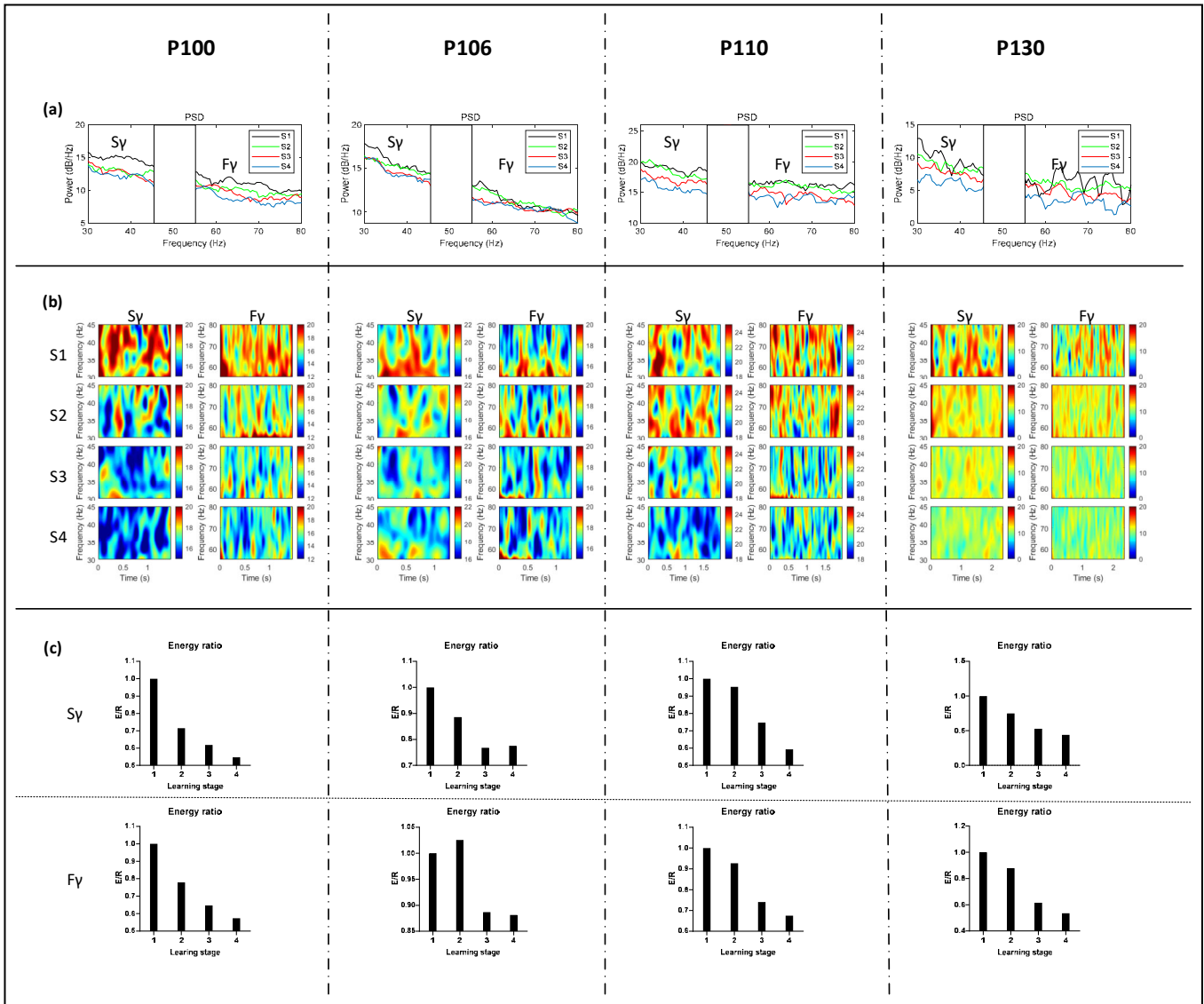

Fig. 3. Results of spectral analysis, from left to right, the pigeon number is P100、P106、P110、P130. (a) Power spectral properties of LFP signals on gamma rhythm. Each power spectrum contains the results of power spectral analysis of four stages during spatial learning. (b) Time-frequency properties of LFP signals on gamma rhythm. From top to bottom, there are four stages of spatial learning of pigeons. The color depth in the time-frequency diagram indicates the energy of the LFP signals on that frequency. (c) Energy ratio of LFP signals in four stages. Above is the energy ratio on slow gamma rhythm, and below is the energy ratio on fast gamma rhythm.

pigeons show similar change trend, observing the power spectrum of LFP signals from the two scales of time and frequency. That is, the power of the LFP signal shows a downward trend not only from low frequency to high frequency but also from the first stage to the fourth stage.

C. LFP Time-Frequency Properties

The time-frequency properties of the LFP signal in the gamma band were analyzed in this paper to reveal the intrinsic relationship between the behavioral performance of the pigeons and the neural activity pattern in Hp along with the spatial learning process. The results are shown in Fig. 3b. According to the qualitative analysis, we can see that the LFP signal energy of the four pigeons decreases with the deepening of spatial learning, whether in $S\gamma$ or $F\gamma$, that is, neural activity in Hp is weakened.

Next, the corresponding quantitative analysis was carried out. We calculated the energy ratio of each pigeon in four stages, and the results are shown in Fig. 3c. Locally, except for the pigeon numbered P106, for the other three pigeons in the process of spatial learning, the energy ratio of the LFP signals is gradually decreasing with the continuous deepening of the learning stage. However, on the whole, the energy ratio of the LFP signals of the four pigeons is decreasing. These results confirm the previous conclusion again.

IV. Conclusion

In this paper, how the neural activity in the Hp changes with the corresponding behavior during spatial learning of the pigeons performing the goal-directed task was explored. From the above results, we can gain some inspiration. When pigeons first arrive in a strange environment, they will continue to explore to familiarize themselves with the surrounding environment so that they can be able to find the goal. In this spatial learning process, pigeons cannot find the goal point at the beginning, and in the end, they can find the goal point easily with the preferred path. From the behavioral point of view, such performance means that pigeons have learned this spatial learning task well. During the gradual learning of pigeons, the neural activity in Hp shows a decreasing trend in gamma rhythm. In the early stage of spatial learning, the neural activity in Hp is more active. However, in the later stage, pigeons have formed spatial memory, without too much brain activity to find the goal, then its neural activity is weakened. That is to say, the goal-directed behavior modulates the neural activity in Hp of pigeons to some extend.

Overall, we have shown that behavioral changes in spatial learning are accompanied by neural modifications in in the hippocampal gamma rhythm. However, this study is not comprehensive enough, and we will do further research from signal scale and brain region scale. At the signal scale, the relationship between the internal multi-channel signals in Hp will be further analyzed, and the changes in the network degree will be analyzed too. At the brain region scale, the changes of neural patterns in other brain regions and the relationship between Hp and other brain regions during spatial learning need to be further explored.

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