The interdependence between motor behavior and cognition: A noise shaping neural coding perspective

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Abstract

Not only the issue of the dissociation/interaction between signal and noise in both spike trains and EEG, but also the issue of the dissociation/interaction between motor functions and cognitive functions have long been a matter of interest. To demonstrate that the two issues are closely related to each other, I here propose a causal relationship between P300 ERP and theta/gamma oscillations based on the noise shaping neural coding hypothesis and the multiple Kalman filters model for spatial cognition. Finally, I shall provide experimental evidence to support the causal relationship between P300 event-related potential, theta oscillation and gamma band fluctuation.

It is widely agreed that the human brain's electrical activity reflects higher cognitive functions such as attention, arousal, and even consciousness. For example, the P300 component of event related potentials has been evoked in tasks where human subjects had to respond to infrequent events while ignoring frequent ones. P300 is an endogenous component of the event-related potential (ERP) that appears as a positive deflection that is largest at centro-parietal electrodes, with a peak latency of approximately 300 ms for simple auditory stimuli. In animals (including monkeys, cats and rats) trained to perform such type of task, P300-like potentials remarkably similar to those in human subjects were found. Several investigators have demonstrated that a task-relevant increase in both amplitude and frequency of the hippocampal theta oscillation is related to the P300 response. Interestingly, a hippocampal P300 is also accompanied by hippocampal gamma oscillation. However, the relationship between P300, theta and gamma oscillations reported in the previous reports is correlational and say little about possible causal mechanisms. Although it is generally accepted that the P300 response is related to cognition, people are not sure exactly what. Moreover, there have long been arguments on overlaps between P300 and covert/overt movement-related potentials. It may prove impossible to disentangle cognitive components like P300 from motor components associated with a required action, where covert verbal reactions such as mental counting can be also considered a motor response. Similarly, since hippocampal theta oscillation was discovered about 50 years ago, it is still under argument whether hippocampal theta oscillation is directly related to motor activity or not. On the other hand, identifying the origin and functional role of neural noise (or on-going activity) may reveal something new and fundamental about how the brain works. Recently, Harris and Wolpert (Nature, 394, 780, 1998) proposed a significant new perspective on neural noise in that they assumed signal-dependent noise in the brain and demonstrated that it can be involved in motor planning. Their model suggests that neural noise can be actively engaged in cognitive process such as optimal path planning. To clarify the causal relationship and its functional significance of P300 event related potential (ERP) and theta/gamma oscillations, we conducted behavioural and electrophysiological experiment using rats trained to perform auditory discrimination oddball paradigm.

Nine male Long Evans rats between 300 and 400 g were housed in individual cages with food and water provided until the behavioural training. Pairs of 80 μm varnish-isolated stainless-steel wires were placed in CA1 region for unipolar recording of the hippocampal field potentials. One week after surgery rats were water-deprived and trained in a chamber by means of oddball paradigms, in which occasional 'target' stimuli have to be detected in a train of frequent 'non-target' stimuli. In a second behavioral task, rats were trained to run spontaneously in a wheel. (see Shin et al, Neurocomputing, 38, 1557, 2001; Shin and Talnov, Brain Research, 897, 271, 2001 for detail methods).

In well-trained rats a significant frequency increase of the hippocampal theta rhythm was found about 300 ms after the odd tone but only if the animal's response was correct. After the non-target tone, no comparable changes have been observed irrespective of the rat's response. In untrained rats any comparable frequency changes after any of the tones no matter how the rat respond were not found. These phenomena could be interpreted as hippocampal theta frequency shift is related to cognitive process (or P300 response). From our video recording of rats' behaviour during oddball paradigm, it was found that the rats moved around sniffing and exploring the front part of the chamber ignoring frequent tones but quickly walking to the water tube after odd tones. Moreover, the duration of theta frequency increase after odd tone was correlated with the quick walking time between odd tones and drinking time in the water tube because no theta rhythm was found during drinking water. In the second behavioural task, theta frequency change was correlated with spontaneous wheel running speed within single trials even when the relationship between mean theta frequency and mean wheel running speed had no significant correlation. Moreover, theta frequency shifts were observed even during spontaneous deceleration periods without involving any cognitive task and learning. As a result, these results support the hypothesis that theta rhythm is related to motor activity and then changes in hippocampal theta rhythm are a consequence of the fact that training changed the characteristic of the motor behaviour. Namely, training in this experiment made rats increase locomotion speed toward the water tube after correct (odd) tone, which results in theta rhythm enhancement in both frequency and amplitude. These results raise a doubt about whether P300 response is really related to cognitive processes because P300 also should be related to motor activity if hippocampal theta rhythm is a source of P300 response.

Traditional theories assume that cognition and motor functions are entirely distinct processes. Its implication is that each can be studied and understood without reference to the other. In the ecological view, however, cognition and motor activities are tightly interlocked processes. Namely, there is a continuous cycle between motor activity and cognition/perception. For example, it is suggested that all discontinuous sensorimotor functioning is designed to take part on return in the cognitive processing of new representations, thus achieving that "original and deep interdependence between movement and thought" by which the close links between psychic anomalies and motor anomalies can also be explained. According to the Kalman filter models of the hippocampus and the parietal cortex, motor command efference copies and sensory feedbacks are engaged in updating of internal representation of environment. P300 may result from the internal state and context estimation using motor efference copies and sensory feedbacks. If so, the overlap of P300 and movement related potential is inevitable because covert and overt movements are the trigger of such updating of internal model. In conclusion, we suggest the causal relationship between hippocampal theta and gamma oscillations and P300 as follows: 1) theta oscillation is covert and overt movement-related signal; 2) the brainstem is the trigger (or source) of theta oscillation; 3) the hippocampus and the frontal/parietal cortex use motor command efference copies (e.g., theta oscillations) for internal state and context estimate; 4) the estimation (or update) process results in the P300 as a by-product; 5) gamma oscillation in vivo can be the signal-dependent noise resulting from the noise shaping neural coding (Shin, Biosystems, in press) and may be engaged in optimal trajectory planning for action.