Effect of Brain Alpha Oscillation on Performance in Laparoscopic Skills Simulator Training

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Abstract

BACKGROUND: Laparoscopic skill involves sensory processing and motor control，which is associated with high-level alpha oscillation of the brain. Neurofeedback (NF) has been reported effective in enhancing alpha oscillation. Our objectives were to assess the alpha oscillation during laparoscopic skills training, and to verify the usefulness of NF in improving the learning efficacy.

METHODS: Sixty medical students without laparoscopic experience were recruited. Multi-channel electroencephalography (EEG) signals were recorded during training of peg transfer task. Training performance was assessed based on the task completion time. All subjects participated in the first experiment comprising eight training blocks and one testing block. Subjects were ranked based on performance: the top 20 subjects were classified as the good performance group and the bottom 20 subjects as the fair performance group. In the second experiment, the fair performance group were randomly divided into the NF and control groups. Spectral analysis of EEG signals was used to calculate alpha power and alpha band coherence. Training performance and EEG alpha powers were compared between the NF and control groups.

RESULTS: In the first experiment, the completion time was significantly faster in the good performance group (62.5±2.8s) compared with the fair performance group (75.0±5.6s) (p<0.05). EEG oscillations showed strong alpha power and alpha coherence in the posterior electrode clusters in the good performance group. In the second experiment, the NF group showed much stronger alpha activity power and coherence compared with the control group. Furthermore, the NF training led to a significant performance improvement from 75.1±5.9 s in the first experiment to 64.3±4.9 s in the second experiment (p=0.003).

CONCLUSIONS: The learning performance of laparoscopic skills varies among individuals. Subjects with good performance results had high alpha power and strong alpha coherence. The alpha enhancement NF increased alpha oscillations, leading to improved learning efficacy.

KEY WORDS: laparoscopic skills; simulation training; surgical education; electroencephalography (EEG); alpha oscillation; neurofeedback

INTRODUCTION

Laparoscopic surgery is a commonly used modality within minimally invasive surgery [1, 2]. Compared with traditional surgery, minimally invasive surgery reduces tissue injury and surgical complications, and accelerates tissue repairation and regeneration to increase the stability of the internal environment and induce faster recovery [3, 4]. Laparoscopic surgery offers different technical challenges compared with traditional open surgery, as it involves limited field of vision, scope of operation, and assistance [4, 5]. Therefore, the learning curve for laparoscopic surgery is longer than that for traditional surgery [6-9].

As laparoscopic surgery is a complex work-related task, a large amount of laparoscopic skills training is required [9, 10]. Laparoscopic skills training with simulation modules is included in the education of medical students and postgraduate residency training, as well as in surgeons' retention exercises [11]. Skill training through teaching innovation is expected to improve the efficacy of laparoscopic skills training. In our experience, individual students achieve different levels of performance after training. The reasons for such interindividual difference are unclear [12]. However, cognitive and educational psychology studies propose that learning efficiency is affected by emotional status and brain activity [13-15].

Electroencephalography (EEG) is a non-invasive method of evaluating brain activity that is extensively applied in educational psychology studies investigating cognitive ability, learning, and working memory [16]. EEG has been used to monitor the influences of emotional and competitive factors on the ability to solve complicated problems [17]. The brain activity reflected by EEG oscillations indicates the synaptic excitation and neuronal excitability, and plays a major role in coordinating inter-areal communication and neuronal collectivity [18-22], aiding the integration of individual neuronal activity into a coherent cognitive process [18, 22, 23]. In particular, alpha oscillations are involved in the specific aspects of cognition, perception, attention, and memory [24-26]. Increases in high alpha band rhythmic brain waves correlate with working memory [27]. Several studies have demonstrated the role of alpha oscillations in the modulation of sensory perception and working memory retention [28-30]. Studies have revealed a relationship between alpha oscillation and spatial working memory performance [31], showing that alpha power is a good indicator of neural excitability [26, 32]. Changes in alpha power are correlated with good or poor performance in sensory information processing during difficult tasks [33-35]. These alpha EEG oscillations are enhanced by neurofeedback (NF), which is a promising technology used to improve training performance, including sensory information processing and working memory [12, 36-38].

The efficacy of laparoscopic surgery training has been studied previously via behavioral comparisons [2, 15]. In contrast, the brain activity and emotional status during laparoscopic simulation training and/or the effect of NF on performance during laparoscopic surgery training have rarely been investigated. In the present study, we compared the alpha oscillation of medical students who were classified as good versus poor learners during laparoscopic skills training, and evaluated the use of NF training during laparoscopic skill training.

MATERIAL AND METHODS

Participants and Ethical Approval

This prospective study was performed in the Laboratory of Neural Engineering, Institute of Biomedical Engineering, Chinese Academy of Medical Sciences & Peking Union Medical College. A total of 60 medical students in their 2nd to 4th year of study who had no laparoscopic experience participated in the present study, including 38 males and 22 females aged 23.4±2.3 years. This study was approved by the local ethics committee of the institute. Informed consent was obtained from all participants.

Apparatus and Tasks

All subjects completed the Fundamentals of Laparoscopic Surgery training course using a simulation box (Limbs & Things Inc. Savannah, GA, USA). The task assessed in the present study was the peg transfer task in which the participants had to manipulate two conventional (straight) laparoscopic graspers to transfer six plastic triangular objects from one side to the other in random order, and then return the six plastic triangular objects to their original places.

Experimental procedure

Each participant completed a 2-day experiment (Figure 1). On the first day, all participants watched an introductory video and completed a warm-up trial before performing eight training blocks of peg transfer practice. Each training block consisted of three training sessions, with each training session comprising one peg transfer task. On the second day, all participants completed a warm-up trial before performing a retention test block comprising three sessions of the peg transfer task.

EEG Recordings and Analyses

EEG was recorded using a NeuroScan system at a sampling rate of 1 kHz and band pass filter of 0.05–100 Hz. A standard EEG cap was applied on the scalp with 64 channels (international 10-20 system) in reference to Cz, while the impedance of all recording electrodes was kept below 10 kΩ. The electro-oculographic and EEG signals were simultaneously recorded, and then underwent off-line processing to remove ocular movements and eye blinks. On each day of the experiment, a pre-task baseline EEG was recorded for 30 seconds at the start time. Continuous EEG was then recorded during the subsequent training and testing blocks.

After the experiments, the EEGLAB toolbox was used to perform the offline analysis of EEG signals [39]. Raw EEG signals were band pass filtered at 1–30 Hz, down-sampled to 100 Hz, average referenced, and baseline corrected using the pre-task recording. Independent component analysis was performed to remove artefacts such as eye blinks and movements, and muscular noise. After removing the EEG channels and intervals, the EEG epochs were segmented in 10-second intervals. Fast Fourier transform with hamming windows was applied to calculate the power spectral density of alpha band EEG in every channel and epoch. The μV^2 power values were calculated by the pop_spectopo.m function in EEGLAB with Welch's power spectral density estimate [39], and then log transformed using the following formula.

$$\log PSD = \log_{10}(1 + PSD) \qquad (1)$$

Three EEG epochs were selected from the start, middle, and end of each training session. The alpha powers of the three epochs were averaged for each block.

The amplitude-squared coherence was used to compute brain connectivity networks, and was calculated using the following formula

$$Coh_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \qquad (2)$$

where $P_{xx}(f)$ and $P_{yy}(f)$ are the power spectral densities of x and y, and $P_{xy}(f)$ is the cross power spectral density of x and y. To compare the difference in the Coherence Net between groups and reduce the effect of inter-subject variability, the difference in the average coherence between groups was plotted.

Performance evaluation and study design

All subjects completed the first experiment comprising eight training blocks performed on the first day and one testing block performed on the second day. The training performance was evaluated by the average completion time of three peg transfer sessions in the testing block. In the first experiment, the 20 subjects with the shortest completion times were classified as the good performance group, while the 20 subjects with the longest completion times were classified as the fair performance group; the remaining 20 subjects were excluded from further analysis.

The fair performance group completed the second experiment 2 weeks after the first experiment. The 20 subjects were randomly divided into the NF group and the control group. The second experiment was conducted in the same way as the first experiment. However, in the second experiment, the NF group received NF training before completing the training blocks on the first day, while the control group did not receive NF training. The steady-state visual evoked potential(SSVEP)-based brain computer interface (BCI) was used as a NF tool. As figure 2 showed, a violet sphere ball was displayed on the middle of computer screen. Three blue switches with stimulation frequencies of 8 Hz, 10 Hz, and 12 Hz were arranged as a control to raise, land, and stop the sphere ball on the screen. These 3 switches served as SSVEP BCI to raise or land the violet sphere ball. The ratio between alpha and bate power was defined as real time neural feedback parameter, which was reflected with the size of sphere ball (from small size in Fig 2 a-c to large size in Fig 2 d-f). The higher the alpha to bate ratio, the larger the radius of sphere ball. During NF training, subjects in NF group were instructed to raise and lower the sphere for 15 minutes using the SSVEP control switches.

Statistical Analyses

In the two experiments, the behavior results (completion time) and EEG alpha powers were calculated for the eight training blocks and one retention testing block for the two groups. One-way analysis of variance (ANOVA) was applied to compare the demographic data, behavior results and EEG alpha powers of the good and fair performance groups in the first experiment. The paired student's t-test was performed to compare the behavior results and EEG alpha powers of the second experiment versus the first experiment. The significance level was set at $P<0.05$.

RESULTS

Demographic information

A total of 60 medical students voluntarily participated this study. The rage of age was narrow so that it is difficult to observe the effect of age on the learning performance. In consideration of gender difference, this study involved more male volunteers (38 of 60 subjects, 63%) than female volunteers (22 of 60 subjects, 37%). In the first experiment, there was no significant difference of age among 3 groups of various performances ($F=1.325$, $P=0.27$ by ANOVA). The gender distribution in 3 groups of various learning performances did not show obvious difference between male and female (Table 1).

Laparoscopic skill training performance

All subjects successfully completed the peg transfer training tasks. In the first experiment, the average completion time of the testing block differed among subjects (mean 70.4±7.7 s, range 56–90 s). The distribution of the completion time of the 60 subjects is shown in Figure 3. Based on the performance in the testing block, the 20 subjects with a completion time of less than 66 seconds were classified as the good performance group, while the 20 subjects with a completion time of longer than 74 seconds were classified as the fair performance group. The average completion time was significantly shorter in the good performance group (62.5±2.8 s) than in the fair performance group (75.0±5.6 s) ($P<0.05$ by analysis of variance). The completion times in the two groups did not significantly differ until training block 6 (Figure 4).

In the second experiment, the NF and control groups each comprised six males and four females. The average completion time of the NF group (64.3±4.9 s) was significantly shorter than that of the control group (73.7±4.8 s) in the testing block (two-tailed t-test, $P<0.01$). The average completion time of the NF group significantly decreased from 75.1±5.9 s in the first experiment to 64.3±4.9 s in the second experiment (paired student's t-test $P=0.003$, $t=4.5$), while the average completion time of the control group was similar in the first experiment (74.6±5.5 s) and the second experiment (73.7±4.8 s; paired student's t-test $P=0.73$, $t=0.34$).

Alpha EEG oscillations

Figure 5 shows the EEG oscillations of the good and fair performance groups in the first experiment. Overall alpha power was calculated by averaging the spectral power of 10–12 Hz in the channels of C3/4, O1/2, PO3/4, and P1–P8. EEG alpha oscillation was significantly higher in the good performance group (overall alpha power 4.7±1.9 μV^2) than the fair performance group (overall alpha power 2.5±1.9 μV^2; t-test $P=0.0012$). EEG alpha oscillation at 64 leads were plotted with contour topographic mapping, which is a commonly used visualization of topographic brain activity. In the topographic map, hot color represents high intensity of EEG activity, while cool color represents low intensity of EEG activity. EEG alpha topographic maps showed different patterns in the two groups. The good performance group had strong alpha power in the posterior electrode clusters (PO7/8, PO5/6, PO3/4, POZ, and O1/2, Ozz), especially in the alpha frequency of 10–12 Hz.

Figure 6 shows the EEG alpha oscillation of the control and NF groups in the second experiment. The NF group had a significantly higher alpha power of 9–12 Hz (overall alpha power 5.7±2.0 μV^2) compared with the control group (overall alpha power 2.7±1.8 μV^2; t-test P=0.0027). The EEG alpha topographic maps of the control group in the second experiment were similar to those of the fair performance group in the first experiment; however, the control group had a high alpha power at CP3/CP/4, reflecting activity in the somatosensory cortex.

Alpha EEG coherence

EEG coherence analysis of the alpha spectrum band (8–13 Hz) was performed in the good and fair performance groups in the first experiment (Figure 7), as well as the NF and control groups in the second experiment (Figure 8).

There was strong alpha coherence (>0.8) in the temporal and occipital lobes in all groups. In the good performance group of the first experiment, coherence >0.8 occurred in C1, C3, CP1, CP3, CP5, TP7, P1, P3, P5, P7, PO3, PO7, and O1 in the left lobe, and in C2, C4, CP2, CP4, CP6, TP8, P2, P4, P6, P8, PO4, PO8, and O2 in the right lobe. In the NF group of the second experiment, coherence >0.8 occurred in C1, C3, CP1, CP3, CP5, P1, P3, P5, P7, PO3, PO7, and O1 in the left lobe, and in C2, C4, CP2, CP4, CP6, TP8, P2, P4, P6, P8, PO4, PO8, and O2 in the right lobe. The alpha EEG coherence network of the NF group in the second experiment showed a similar pattern to that of the good performance group in the first experiment.

The alpha coherence in the control group in the second experiment was almost the same as that in the fair performance group in the first experiment, with coherence >0.8 in C1, C3, CP1, CP3, CP5, P1, P3, P5, and PO3 in the left lobe, and in C2, C4, CP2, CP4, CP6, P2, P4, P6, PO4, PO8, and O2 in the right lobe.

In comparison with the coherence net of the fair performance group in the first experiment, the group with good performance showed enhancement alpha coherence in C1, C3, C6, CP3, CP5, F5, P3, P4, P5, P6, P7, PO4, POz, and TP7 (figure 7). In the second experiment, the enhancement alpha coherence between NF group to control group can be seen in AF3, AF7, C4, C6, Cz, CP1, CP5, CP6, CPz, F3, F4, F5, F6, F7, FC5, FT7, P1, P2, P3, P4, P5, P6, P7, P8, PO3, PO7, Pz, O1, Oz, TP7, and TP8. Based on Brodmann areas analysis [40], the increasing coherences in both good performance group of the first experiment and NF group of the second experiment indicated exciting activity of somatosensory and associated function (C1, C3, CP3, CP5), visual and associated function (P7, PO4, POz, TP7, P3, P4, P5, P6) and integration (F5, F6, AF3, AF7).

DISCUSSION

The present study compared the features of alpha EEG oscillations in students with different performance abilities during laparoscopic skills simulator training. Students with good performance in laparoscopic skills training had higher alpha EEG power than students with fair performance. The group with good training results had strong alpha EEG coherence in the temporal and occipital lobes. Subsequently, NF training of the students with fair performance resulted in increased alpha power and strength of alpha coherence, in association with good training results in comparison to controls. This suggests that students with higher alpha power were quicker to learn laparoscopic skills during training than students with lower alpha power. Most importantly, the present study demonstrated the potential of alpha EEG NF to enhance the efficacy of laparoscopic skills simulator training.

With the rapidly increasing popularity of laparoscopic surgery, additional training in a simulated environment has become a routine and cost-effective protocol for teaching and testing laparoscopic skills [2, 15]. The training tasks usually include skills such as camera navigation, clipping, peg transfer, cutting, knot tying, and needle driving. The present study used the peg transfer task as the experimental task [2, 6, 15]. Phenomenologically, peg transfer is a typical laparoscopic skill that engages visual spatial cognition, depth perception, sensation perception, fine motor function of the hand for ambidexterity, and hand-eye coordination [2, 8]. The training performance was evaluated based on the task completion time in the retention testing block performed 1 day after the subjects had completed eight training blocks. The task completion time is an objective evaluation that reflects the retainment of experiences based on the ability to process and maintain information for a short period of time (the working memory). The completion time data of the 60 subjects showed normal distribution. The completion time significantly differed between the good and fair performance groups from training block 6 onwards. Most importantly, the fair performance group achieved good performance after NF training, while the control group who did not receive NF training maintained the same fair performance level.

Analysis of the alpha EEG oscillations of subjects during the first experiment showed that higher alpha power was associated with good performance during laparoscopic skills training. The results from the retention testing block reflect the performance of the working memory, which is correlated with alpha EEG oscillatory activity [31]. The alpha EEG features in the good performance group revealed a high alpha power in the 10–12 Hz range, which is believed to respond to specific task demands such as memory processing or intelligence-related demands [41]. The correlation of high alpha power with good results in the retention testing block is aligned with the prominent modulation of alpha power during retention [31, 42].

The EEG alpha topographic maps in the good performance group showed strong alpha power in the posterior electrode cluster. This is believed to be related to the demands of the brain neurology functions required to perform laparoscopic skills, including cognitive, associative, and autonomous visuospatial processing, sensory processing, and motor control. The peg transfer task involves visual perception, somatosensory perception, and fine motor control of the hand; these skills are associated with the relevant areas of the brain cortex, which were observed using electrodes on the scalp to monitor the temporal and occipital lobes. In the group with good performance in the training and testing blocks, the role of alpha oscillations in the occipital lobes is suggested by the good performance of spatial attention [26, 29, 30]. The nature of the peg transfer task involves primary sensory modulation and hand motor modulation; this process is considered to involve the modulation of the primary somatomotor, somatosensory, and visual areas.

The neurophysiological results of alpha coherence showed relatively high alpha band activity in the temporal and occipital lobes, and low alpha band activity in the other lobes. These local alpha band oscillation findings agree with previous findings regarding the inhibition and disinhibition of corresponding local cortical processing [18]. High alpha oscillations act to suppress processing that is irrelevant to the task being performed, while active-processing is facilitated [18, 27].

The second experiment was performed to further show the alpha oscillation features in association with laparoscopic skill performance, and to demonstrate the effect of alpha enhancement NF on the learning efficacy of laparoscopic skills. NF was performed to increase the alpha activity before training, and this effect was maintained in subsequent training blocks [43]. In the second experiment, the NF group successfully increased their alpha power in comparison with control group, especially regarding high-level somatosensory alpha oscillations. In addition, the alpha topographic maps and coherence of the NF group showed similar patterns to the brain activity in subjects who achieved good performance in the first experiment. In the second experiment, the NF group performed better than the control group. As there was a washout period of 2 weeks between the first and second experiments, we believe that very little of the laparoscopic skill acquired in the first experiment remained by the time the subjects completed the second experiment; this theory was supported by the similar performance results achieved by the control group in the first and second experiments. In contrast, the significant improvement of performance in the NF group provides evidence for the true effect of alpha enhancement NF. The results of the second experiment demonstrate that NF enhances alpha oscillations and leads to high-level alpha oscillations. NF excise enhanced alpha activities in more areas than target brain areas in regarding somatosensory, motor and visual function during laparoscopic skills simulator training. Those extra activation of alpha coherences in NF group had redundant effects. Anyway, the alpha enhancement NF provided top-down modulation to improve the learning efficacy of laparoscopic skills. This finding is consistent with a previous study that demonstrated an improvement of learning efficacy with enhancement of alpha oscillation, and a reduction of learning efficacy with depression of alpha oscillation [12].

The present study had limitations. The learning task assessed in the present study is only one of the laparoscopic skills. The behavior data showed sufficient evidence to support the association of alpha activity with motor skill practice and working memory processing. Further study could expand the use of NF in learning other laparoscopic skills, such as camera navigation, cutting, suturing, knot tying, and clipping. This study involved 60 medical students in a small range of age difference. The sample size of 60 subjects with imbalance of gender distribution, this study did not find effect of age and gender factors on learning performance， which is not agree with findings in previous study[44]. In further investigation on the good learner of laparoscopic skills, personal characteristics of subject should be considered beside age and gender.

In conclusion, the performance in laparoscopic skills training was associated with alpha oscillation in the posterior electrode clusters. Subjects with good performance in laparoscopic skills training had high alpha power and strong alpha coherence. NF may effectively enhance the alpha oscillation and improve the learning efficacy of laparoscopic skills.

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Table 1 Demographic information

Subjects number		Gender			
	Number (Age)	Male		Female	
		Number	age	Number	age
Experiment 1	60 (23.4±2.3)	38	23.1±2.5	22	23.9±1.7
Good performance	20 (23.1±2.6)	13 (34%)	22.9±2.7	7 (32%)	23.7±2.4
Moderate performance	20 (24.0±1.9)	13 (34%)	23.9±2.1	7 (32%)	24.1±1.7
Fair performance	20 (23.0±2.2)	12 (32%)	22.5±2.6	8 (36%)	23.8±1.0
Experiment 2	20	12		8	
Control group	10 (23.1±2.4)	6 (50%)	22.8±2.0	4 (50%)	23.5±1.3
NF group	10 (22.9±2.1)	6 (50%)	22.2±2.4	4 (50%)	24.0±0.8

Figure legends

Figure 1 Experiment protocol

Figure 2 Illustration of neurofeedback training

Figure 3 Distribution of the completion times of all subjects during the testing block

Figure 4 Completion times of the good and fair performance groups in the training and testing blocks

Figure 5 Electroencephalography frequency spectrum difference of the fair performance group (a) and the good performance group (b) in the training and testing blocks

Figure 6 Electroencephalography frequency spectrum of the control group (a) and the neurofeedback group (b) in the training and testing blocks

Figure 7 Alpha electroencephalography coherence in the good and fair performance groups in the first experiment (red lines indicate coherence>0.8)

Figure 8 Alpha electroencephalography coherence in the neurofeedback and control groups in the second experiment (red lines indicate coherence>0.8)