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Electroencephalogram phase gradients reflect the differences in neural processing during online versus face-to-face learning

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Abstract— We evaluated the cognitive differences between online and face-to-face learning using electroencephalogram (EEG) measurements with EEG phase gradient (PG) analysis on a scalp map. The results indicated that during online learning, in contrast to face-to-face learning, the beta-band (15–30 Hz) PG in the anterior-to-posterior direction were significantly increased. Of note, this pattern was similar to those observed during resting period. This characterized neural processing during learning, suggesting that online lectures evoke more relaxing states similar with resting than face-to-face lectures that would evoke some certain types of activations in the social context.

1. Introduction

During the coronavirus disease 2019 (COVID-19) pandemic, numerous schools transitioned to online, rather than face-to-face, learning to prevent the spread of the virus. Online lectures have clear advantages in convenience by allowing students to learn from home, but there are also concerns regarding the decrease in participants' satisfaction with the courses and their lecturers [1, 2]. To design more effective educational programs, it is essential to understand the differences in participants' cognitive states during online learning compared to traditional face-to-face learning.

Electroencephalogram (EEG) measurements are thought to be an effective method with which to evaluate the differences in cognitive states during online and face-to-face learning, and have been introduced in the assessment of participants' cognitive states in the classroom [3, 4].

The major obstacle to obtaining EEG measurements during face-to-face learning is the presence of motion artifacts during recording, due to nodding, head-titling, and writing, as a few examples. Traditional laboratory EEG experiments usually require head- and eye-fixed conditions to avoid electrical changes from brain waves (e.g., eyeballs are highly electrically polarized and their movement causes electric potential over the scalp, and the physical movement of electrodes and lines also produces large movement-related potentials contaminating the measured signals), while EEG measurements during lectures require head and eye movement-free conditions to maintain natural educational settings.

Such an EEG index, the EEG phase gradient (PG), which goes over the scalp, is thought to be stable against motion artifacts which simultaneously contaminate a limited number of electrodes with large amplitudes. More importantly, according to our connectome-based whole brain network simulation [5], PG is thought to reflect global activations of functional brain networks (e.g., salience network and resting-state networks) and to be associated with the modification of information transfer among brain regions based on the "communication-through-coherence mechanism [6]". PG is associated with EEG propagation waves on cortical surfaces [7] for which such traveling wave analysis has also been utilized to analyze scalp EEGs [8, 9].

In the present study, we compared participants' cognitive states during online and face-to-face learning using EEG measurements and subsequent PG analyses, which are associated with the global state of the brain networks as a stable measure against motion artifacts during learning.

2. Methods

2.1. Participants

A total of five right-handed male participants (mean ± SD:20.4 ± 1.3 years old) were recruited via poster and e-mail advertisements at Future University Hakodate. All of the participants had been attending online lectures for at least six months, and each participant provided informed consent prior to participation. The protocol for the present study was approved by the Ethics Committee of Future University Hakodate (ID:2021005, approval date: Nov. 25, 2021).

2.2. Stimuli

The present study included two lecture sections, "Language" and "Neurotransmitter," which were taken from a

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university lecture termed ”Brain Science” (for fourth-year students at Future University Hakodate). These were expected to be relatively independent of pre-existing knowledge for participants who did not attend the lectures, and were modified to include an 8-min lecture (using 13 and 11 slides), a 5-min examination (with 5 fill-in and 5 multi-choice questions), and a 10-min practice session (drawing of semantic network and predicting neurotransmitter activations in various situations).

2.3. Procedure

Each participant attended two 8-min lectures (online and face-to-face), of which order of their lecture-types and contents were randomized for each participant. Participants attended the online lecture using their own notebook computer (11–14-inch display) with a videoconferencing application, during which a lecturer presented his lecture online by screen-sharing his slides while using a camera showing his face. During face-to-face lectures, the lecturer and the participants sat facing each other at a 120-cm table on which a 23.5-inch display was placed to show the lecture slides. During each lecture, the participants were instructed to use a pencil and a notebook, as is standard for in-person lectures at the university. Immediately after each lecture, the participants performed the 5-min examination and then attended 10-min practice session. Additionally, each participant performed a 3-min resting period with their eyes closed prior to each lecture. After completing the lecture and post-lecture activities, the participants were instructed to use a 5-points scale to answer questionnaires regarding their interests, pre-existing knowledge, and the difficulty of the two lectures.

2.4. EEG Data Aquisition and Pre-processing

EEG and electrooculography (EOG) data were acquired using Ag/AgCl electrodes with an EEG amplifier (Avatar EEG 8ch, Electrical Geodesics, Inc.), referenced to the right earlobe at a sampling rate of 500 Hz. For each participant, five electrodes were mounted on the scalp using the standard 10–20 system (F3, F4, Cz, P3, and P4 electrodes), while three EOG electrodes were affixed above the nasion and below the outer canthi of the eye.

The pre-processing and data analysis pipeline, described herein, are shown in Fig. 1a. First, raw EEG and EOG signals were bandpass filtered using a zero-lag Butterworth filter (1–40 Hz, -12 dB/octave roll-off) and a notch filter (50 Hz). Second, ocular artifacts were reduced via a regression subtraction algorithm [10] using horizontal and vertical EOG signals. Third, bad periods rejected from the subsequent analysis were determined using 200-ms before and after time points with an amplitude > 50 μV in any of the ocular artifact-corrected potentials. Finally, instantaneous spectral signals were calculated using a bandpass filter and a Hilbert transformation, where the spectral bands selected for analysis were the delta (1–3 Hz), theta (4–8 Hz), alpha (9–13 Hz), beta (15–25 Hz), and gamma bands (> 40 Hz). In the subsequent analysis, data points from the spectral phase and amplitude were sampled with a 0.5-s interval, and excluding bad periods, were analyzed.

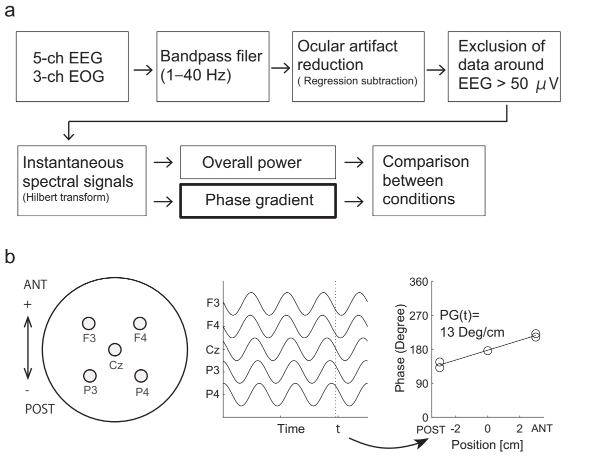

Figure 1: Data analysis: (a) pre-processing and statistical analysis pipeline; (b) electrode alignment (electrodes F3, F4, Cz, P3, and P4) and EEG phase gradient (PG). The PG in a frequency band at time t is defined by the slant of the EEG phase to the electrode positions in the anterior (ANT)-to-posterior (POST) direction.

2.5. EEG Data Analysis

The spectral signals were analyzed to evaluate the participants’ cognitive state during various lecture activities. PG was defined in the anterior-posterior axis, where PG in the anterior-to-posterior direction (i.e., phases of the anterior electrodes are later than those of the posterior electrodes) is positive (Fig. 1b). The PG at time t is defined by the slant of linear regression from the location (-3 cm for F3 and F4, 0 cm for Cz, and 3 cm for P3 and P4) to instantaneous phases ($\theta_{F3}(t)$, $\theta_{F4}(t)$, $\theta_{Cz}(t)$, $\theta_{P3}(t)$, and $\theta_{P4}(t)$). Other PG directions, such as the left-to-right direction, were excluded from the analysis because it was thought that the right-earlobe reference might affect the spatial pattern of the EEGs in the left-to-right axis.

A statistical analysis was performed to compare (1) the three stages of the lectures (resting, lecture, and practice/examination) and (2) the types of lectures (online and face-to-face). The mean values of the PGs (and global power) of each condition were individually evaluated using t-values, which were integrated as the results of group-level analysis.

3. Results

3.1. Examinations and Post-task Questionnaires

Examination scores for the ”Language” lecture ranged from 0.7 to 0.8 (mean ± SD:0.72 ± 0.27), while those

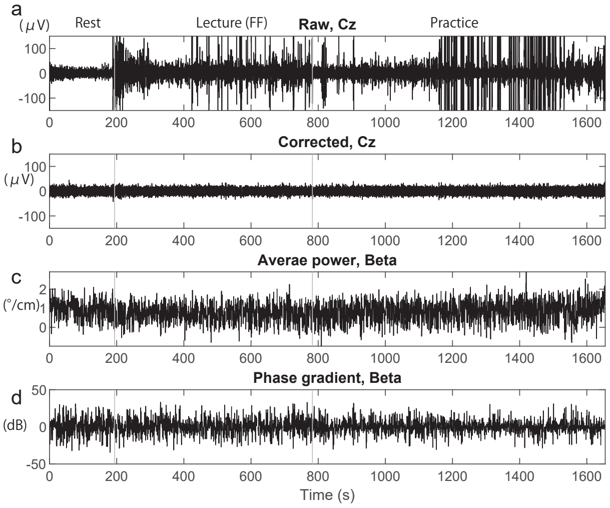

Figure 2: Temporal evolution of EEG data: (a) raw EEG data from central electrode (Cz), for which vertical grey lines indicate the border of each stage of the task; (b) EEG data of the Cz electrode after correcting of ocular artifacts and excluding rejected periods define by > 50 μV threshold; (c) phase gradient in beta-band oscillation; and (d) average power of the beta-band oscillation of all channels.

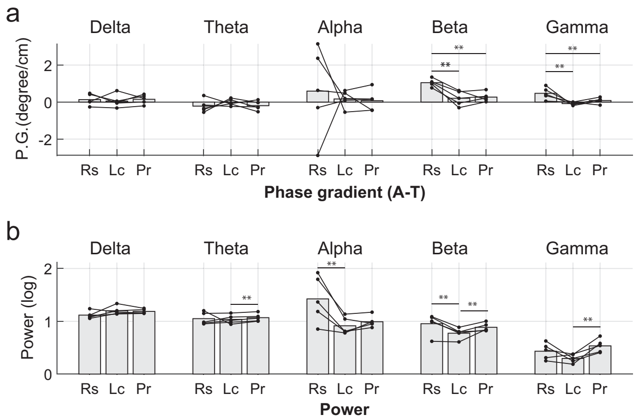

Figure 3: EEG phase gradient and averaged power during resting (Rs), lecture (Lc)(including both face-to-face and online), and practice (Pr) periods: (a) phase gradients in each frequency bands, for which solod lines indicate individual results, bar plots indicate the average of the individual data, and asterisks indicate statistical significance (*: $p < 0.05$, **: $p < 0.01$); (b) averaged powers of all electrodes in each frequency bands.

for the "Neurotransmitter" lecture ranged from 0.6 to 0.9 (mean ± SD:0.70 ± 0.25), with no significant difference between the scores ($t(4) = 0.12$, n.s.). The five-point scores for the post-lecture questionnaires regarding interest, pre-existing knowledge, and difficulty for the "Language" and the "Neurotransmitter" lectures showed no significant difference ($t(4)$: -0.57, -0.46, and 0.67, respectively). These results suggest that the participants' mental efforts during the two lectures were similar, and the EEG data during the two lectures were thought to be comparable.

3.2. PGs During Resting, Lecture, and Practice Periods

Fig. 2a shows the temporal evolution of the raw EEG data at the central electrode (Cz) during the rest, lecture (face-to-face), and practice periods, where large changes in potential were associated with eye blinks, although other motion artifacts could also be included. After preprocessing for artifact reduction (Fig. 2b), stable changes in the potentials were obtained. The PG and averaged power were calculated using the corrected EEG signals from the five electrodes (Figs. 2c and 2d). These values were independent, and the correlation coefficient between PG and power were calculated as 0.01 (3237 time points, n.s.).

PGs in the beta-band oscillations showed significant differences between the resting and lecture periods (integrating face-to face and online) ($t(4) = 6.86$, $p < 0.01$), and also between the resting and practice periods ($t(4) = 5.45$, $p < 0.01$). The PG in the gamma-band oscillation between the resting and lecture periods was significantly different ($t(4) = 3.19$, $p = 0.02$), and also between the resting and practice periods ($t(4) = 2.89$, $p = 0.03$). These results indicate that during the resting period, the beta- and gamma-band oscillations in the frontal regions tended to be earlier than those in the posterior regions.

The alpha-band EEG power during the rest period was significantly increased compared to that during the lecture period ($t(4) = 3.74$, $p = 0.01$). The beta-band EEG power was also significantly different between the rest and lecture periods ($t(4) = 4.08$, $p = 0.01$) and between the lecture and practice periods ($t(4) = -2.99$, $p = 0.03$). These results indicated that the rest-related increase in alpha-band oscillation is a well-known phenomenon, therefore indicating that the artifact reduction procedure worked properly, at least in this frequency band.

3.3. Comparison Between Online and Face-to-Face Lectures

PGs in the alpha-band oscillation during online lectures were significantly smaller than those during face-to-face lectures ($t(4) = -6.59$, $p < 0.01$), as well as between the resting and practice periods ($t(4) = -6.59$, $p < 0.01$), whereas PGs in the beta-band oscillation during online lectures were significantly larger than those during face-to-face lectures ($t(4) = 4.26$, $p = 0.01$) (Fig. 4a). There was no significant change, however, in the EEG power between the online and face-to-face lectures (Fig. 4b).

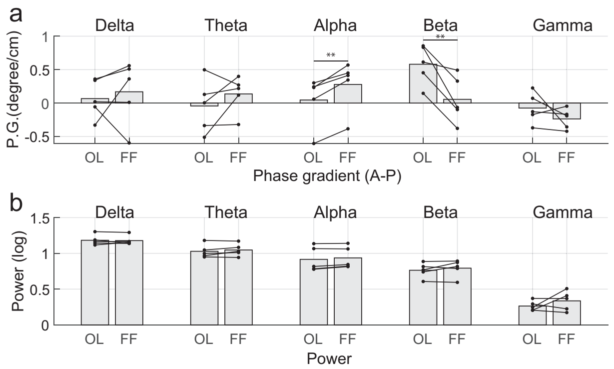

Figure 4: Comparison between online (OL) and face-to-face (FF) lectures: (a) phase gradients in each frequency band; (b) averaged powers of all electrodes in each frequency band.

4. Discussion

PG analysis successfully detected differences in the alpha- and beta-band oscillations during online and face-to-face lectures (Fig. 4a). In comparison with the beta-band PG increase during the resting period (Fig. 3a), the cognitive state during online lectures was thought to be rather similar to that during the resting period. Since examination scores for online and face-to-face lectures were not significantly different ($t(4) = -0.55$, n.s.), it was thought that certain types of activations in the social context, as opposed to the lecture content itself, were evoked during face-to-face lectures. These results suggest that online lectures have advantage that participants can learned with relaxed cognitive state.

In different from the beta-band PGs, the alpha-band PGs have been extensively investigated. In agreement with a prior report on alpha waves during eye-closed resting period [8], the current results on the alpha-band PGs during the resting period varied among participants, as two of the five participants showed a strong anterior-to-posterior gradient, while one participant showed an opposite phase gradient (Fig. 3a).

The present study has three limitations. First, the functional interpretation of PGs was limited due to the small number of previous reports on PGs. Second, the number of the participants in the current study were relatively small (five participants). However, the individual tendency of PGs in the results appeared quite consistent among the individuals without including obvious outliers. Third, the advantage and disadvantage of online and face-to-face lectures should be more comprehensively investigated; for example, the level of the understanding of the lecture contents and its long-term memory would be important for the future investigation.

In conclusion, the current study showed the importance of the PG analysis that could evaluate cognitive aspects which are different from results shown by the standard spectral power analysis. Further investigation using the PG analysis would be important for the complete understanding of the cognitive states during lectures.

Acknowledgments

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