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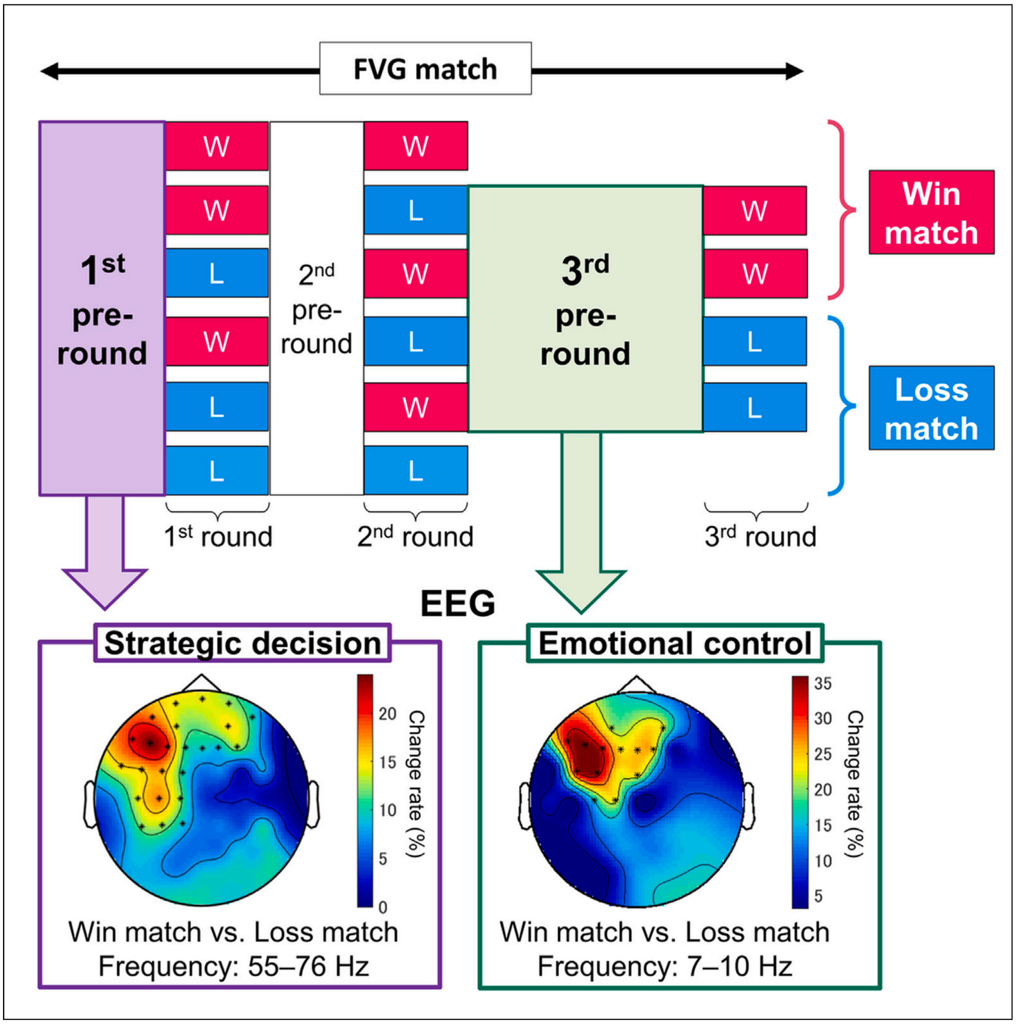

Sorato Minami, Ken Watanabe, Naoki Saijo, Makio Kashino

sorato.minami.yg@hco.ntt.co.jp

Highlights

Winners have increased frontal gamma power in the first pre-round of a match

Winners have increased frontal alpha power in the third pre-round of a match

Individual differences in strategic decisions correlated with frontal gamma power

Individual differences in emotional control correlated with frontal alpha power

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Neural oscillation amplitude in the frontal cortex predicts esport results

Sorato Minami,[1,3,*] Ken Watanabe,[1,2] Naoki Saijo,[1] and Makio Kashino[1]

SUMMARY

In competitive matches, strategic decisions and emotional control are important. Relevant cognitive functions and corresponding neural activities in simple and short-term laboratory tasks have been reported. Brain resources are intensively allocated in the frontal cortex during strategic decision-making. The suppression of the frontal cortex with alpha-synchronization optimizes emotional control. However, no studies have reported the contribution of neural activity to the outcome of a more complex and prolonged task. To clarify this issue, we focused on a fighting video game following a two-round first-pass system. Frontal high-gamma and alpha power in the first and third pre-round periods, respectively, were found to be increased in a winning match. Furthermore, inter-participant variations in the importance of strategic decisions and emotional control in the first and third pre-round periods were correlated with frontal high-gamma and alpha power, respectively. Therefore, the psychological and mental state, involving frontal neural fluctuations, is predictive of match outcome.

INTRODUCTION

It is important to understand the determining factors for winning a match between skilled athletes. It has long been believed that specific psychological and mental states are essential for interpersonal competitions.[1–4] E-sports, which has been gaining attention as a new form of competition in recent years, is played in a virtual space that is less affected by physical differences such as height and muscle mass.[5,6] Therefore, the importance of psychological and mental aspects is emphasized in e-sport matches. Recent studies on e-sports have reported the importance of strategic decisions and emotional control in matches. For example, players make sequential and dynamic decisions in e-sports by interacting with their environment. As the gameplay progress, the initial strategy is refined over time.[7] In addition, intense competition in e-sports provides emotional experiences for players. Players self-regulate their emotions through various approaches in the face of competition.[8]

Previous studies reporting simple visuomotor tasks or single sports action, which refers to basic movements performed by an individual in a short period in interpersonal competitions, have provided insights into the neural activity associated with fundamental cognitive functions constituting the aforementioned cognitive abilities. The neural activity in the frontal cortex increases during the processing of subjectively difficult tasks. In this case, brain resources are intensively allocated to deal with new problems, unusual situations, and unexpected events.[9–13] In addition, the dorsolateral prefrontal cortex (DLPFC) has been suggested to be involved in the strategic selection of tasks that require a high level of strategic ability, similar to e-sports.[14] On the contrary, well-trained individuals utilize alpha-synchronization to suppress neural activity in the frontal cortex to optimize the processing of subjectively less challenging tasks.[9,11–13,15–23] This temporary reduction in frontal cognitive function allows athletes to optimize their level of pressure and anxiety during a performance. As a result, they can produce automatic behavioral responses quickly and effortlessly. These neural activities in the frontal cortices can be considered a neural biomarker for optimal performance.

Although relevant cognitive functions and related neural activity have been reported in simple and short-term laboratory tasks, the contributions of actual neural activity to more complex and prolonged task have not been adequately examined. The predictability of pre-observed neural activity for long-term future outcomes has been limited to cognitive states and characteristics in environments that do not require specific problem-solving, such as cognitive preferences[24–26] clinical outcomes,[24,27] cognitive state transitions,[28]

[1] NTT Communication Science Laboratories, 3-1, Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan

[2] School of Fundamental Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo 169-8555, Japan

[3] Lead contact

*Correspondence: sorato.minami.yg@hco.ntt.co.jp

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and trends in task-related neural responses.[29] It is not yet clear whether the contribution of pre-observed neural activity can be adapted to the outcome of long-term continuous and complex behavior toward some competitive goal. To this end, we focused on a fighting video game (FVG) to clarify this problem. FVG matches are played with no visuomotor action in the pre-round period, followed by an action-oriented round period; therefore, they are well suited for examining the relationship between match outcome and neural activity measured in a noise-free environment.

In this study, we first confirmed whether skilled players share common perceptions about the importance of the strategic decision and emotional control during the match following a two-round first-pass system. Through a questionnaire, we verified that skilled players perceive the high importance of the strategic decision-making in the first pre-round period of a match and of emotional control in the third pre-round period. Next, we recorded the neural activities during pre-round periods in different situations during an FVG match with a mobile electroencephalogram (EEG). By focusing on the frontal areas, we examined the neural oscillations associated with the match outcome. The results showed that increased frontal high-gamma power in the first pre-round period was related to the outcome of the match. Alternatively, increased frontal alpha power in the third pre-round period was also related to the outcome of the match. Furthermore, there was a correlation between the inter-participant variations of subjective indices and frontal neural oscillations in the first and third pre-round periods, respectively. This finding indicates that the performance of skilled e-sport players is predicted by psychological and mental states accompanied by fluctuations in frontal neural oscillations.

RESULTS

Cognitive activities in the pre-round period common to advanced players

To determine the extent to which neural activity, in relation to strategic decision-making and emotional control, contributes to a win or loss in match formats, we used an FVG, which requires different types of psychological and mental state depending on the match phase. The match consisted of repeating the round period and pre-round period, following a two-round first-pass system (Figure 1A). Preliminary questionnaires before this study investigated what cognitive activity of advanced FVG players was predominant during the pre-round period in the match. Fifteen advanced FVG players were asked open-ended questions about their cognitive state in the pre-round period. Fourteen of the 15 players consistently stated that both strategic decision making and emotional control were important for winning a match. As examples of strategic decisions, "Guessing attack patterns that the opposing player dislikes based on the opponent's character type" (11/15) and "Imaging specifically how I will act during the next round" (9/15) were mentioned with high frequency. As examples of emotional control, "When I lose a round, I try not to be aware of negative emotions as much as possible" (9/15) and "I try to keep a normal mind, especially in the third pre-round when pressure is likely to be applied" (8/15) were frequently mentioned. Furthermore, none of the participants perceived the pre-round period as some sort of "break time". There were only a few references to cognitive states (recalling techniques: 1/15; body relaxation: 1/15) other than strategic decision and emotional control across participants, and no direct references to alertness or attention. Based on the preliminary questionnaire results, the main cognitive activities during the pre-round period were summarized as follows. The first is a strategic decision, which is inferring the effective action pattern for the next round based on the opponent's characteristics. The second is emotional control, which is the act of consciously suppressing mental agitation (anxiety about losing) caused by pressure at a critical phase of the match, to perform as usual during the round.

Changes in the degree of success of strategic decision and emotional control at each pre-round period of a match

We confirmed whether skilled players share common perceptions regarding the importance level of strategic decision-making and emotional control during the match. It was assumed that players make strategic decisions and emotional control with different specific weights depending on the phase of the match following a two-round first-pass system. Twenty participants completed a leading questionnaire after all experiments (See "questionnaire" in "STAR Methods" for more information on the questionnaire). The questions were framed assuming that the participant was the winner. We quantified the degree of success of strategic decision-making and emotional control in each pre-round period. Conditional differences in the strategic decision and emotional control at five possible pre-round periods within a single match (Figure 1B) were assessed by one-way repeated ANOVA. As differences were significant, Bonferroni correction for two-tailed paired *t*-tests was conducted between each pair of the five pre-round periods. Higher

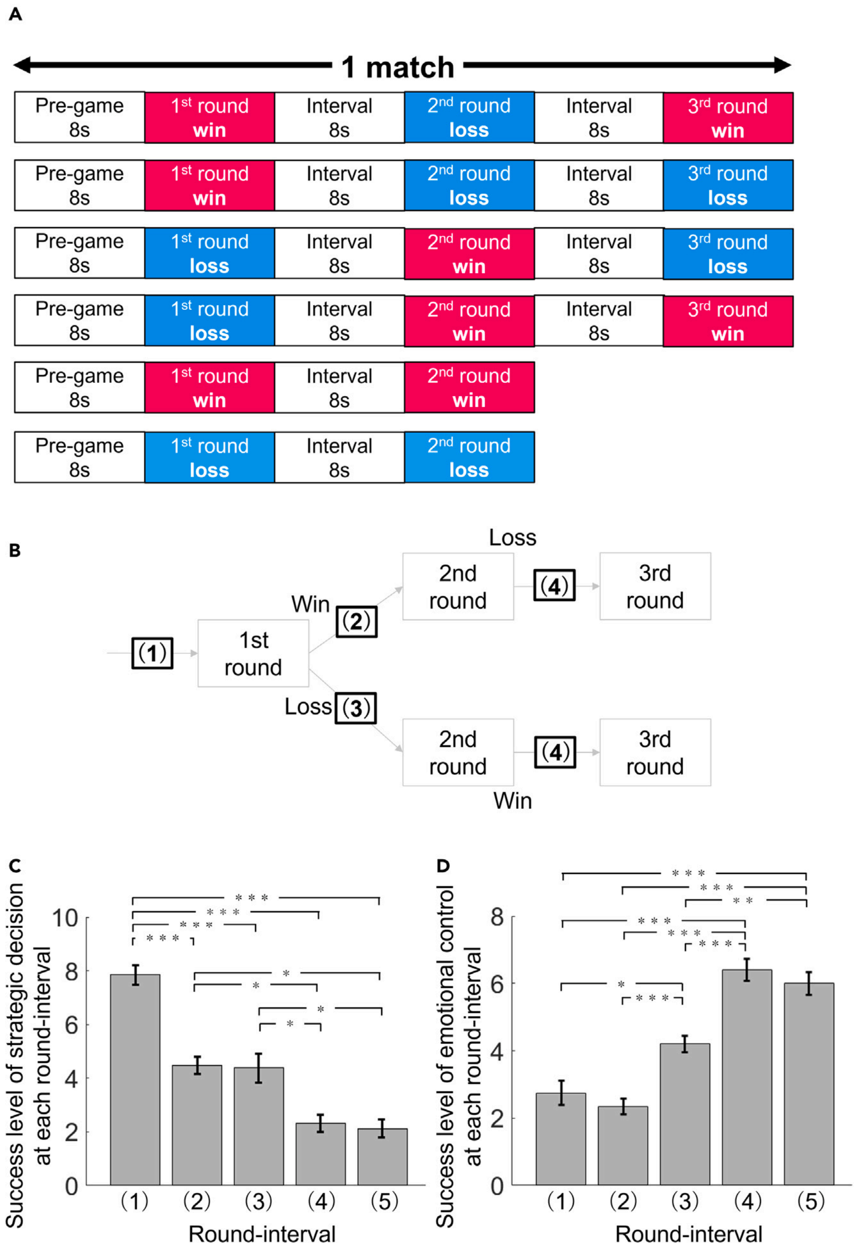

Figure 1. The branching patterns of one match following a two-round first-pass system and changes in the degree of success of strategic decision and emotional control at each pre-round period of a match

(A) A match in a fighting video game (Street Fighter V) consists of the repetition of a pre-round period and a round period. The pre-round period was defined as the 8-s period just before the signal to start the round. One match in the experiment was played according to a two-round first-pass system. The branching patterns are as shown in the figure. A single match includes a total of six possible win or loss patterns (A).

(B) The success level of strategic decision and emotional control at each pre-round period of a match were investigated through questionnaires (B).

(C) The subjective index of strategic decision was highest at the first pre-round period and lowest at the third pre-round period (C).

(D) Conversely, the subjective index of emotional control was lowest at the first pre-round period and highest at the third pre-round period (D). The numbers on the horizontal axis of the bar graph correspond to the pre-round period numbers in the top figure. Error bars represent the standard error of the mean. Statistical significance is indicated at *p<0.05, **p<0.01, ***p<0.001.

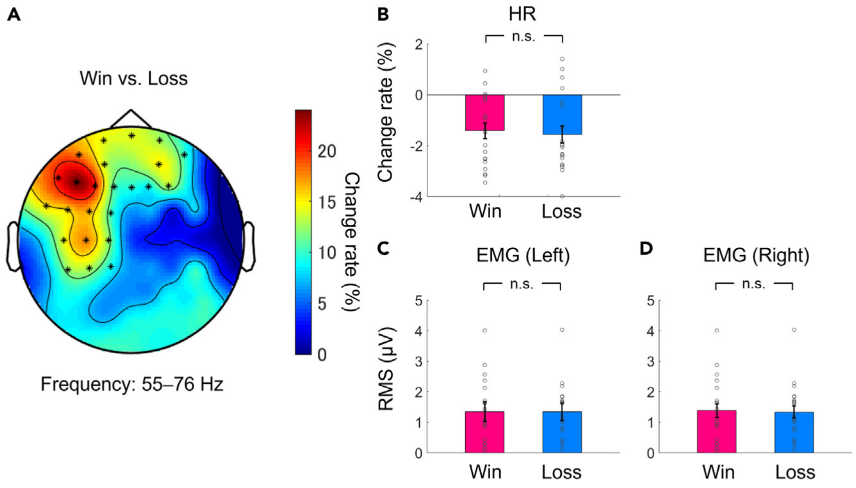

Figure 2. Changes in neural activity and physiological status at the first pre-round period

(A–D) Parameters during the first pre-round period with the highest success level of strategic decision: the left panel shows topographic maps of differences in the amplitude of neural oscillations between winning and losing a match. A cluster-based permutation test was performed, and high-gamma (55–76 Hz) power of the frontal area significantly increased in the win condition (A). The heart rate (B) and left (C) and right (D) EMG did not significantly change between the win and loss conditions. Asterisks in the topographic map indicate clusters of channels that showed a significant increase. Error bars represent the standard error of the mean. Statistical significance is indicated at $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$.

performance of strategic decisions was observed in the earlier pre-round periods as shown in Figure 1C: $F(4, 76) = 32.22$, $p<0.001$; 1 versus 2, $t(38) = 7.09$, $p<0.001$; 1 versus 3, $t(38) = 5.37$, $p<0.001$; 1 versus 4, $t(38) = 10.13$, $p<0.001$; 1 versus 5, $t(38) = 10.10$, $p<0.001$; 2 versus 3, $t(38) = -0.44$, $p = 1.00$; 2 versus 4, $t(38) = 3.56$, $p = 0.010$; 2 versus 5, $t(38) = 3.41$, $p = 0.015$; 3 versus 4, $t(38) = 3.33$, $p = 0.019$; 3 versus 5, $t(38) = 3.20$, $p = 0.027$, 4 versus 5, $t(38) = -0.20$, $p = 1.00$. In contrast, higher performance of emotional control was observed in the later pre-round periods as shown in Figure 1D: $F(4, 76) = 38.12$, $p<0.001$; 1 versus 2, $t(38) = 0.94$, $p = 1.00$; 1 versus 3, $t(38) = -3.40$, $p = 0.020$; 1 versus 4, $t(38) = -7.65$, $p<0.001$; 1 versus 5, $t(38) = -6.61$, $p<0.001$; 2 versus 3, $t(38) = -5.58$, $p<0.001$; 2 versus 4, $t(38) = -10.25$, $p<0.001$; 2 versus 5, $t(38) = -8.86$, $p<0.001$; 3 versus 4, $t(38) = -5.54$, $p<0.001$; 3 versus 5, $t(38) = -4.35$, $p<0.001$, 4 versus 5, $t(38) = 0.86$, $p = 1.00$. An open-ended question about the pre-round period was also asked just before the above leading question. It was confirmed that all of the participants mentioned both strategic decisions and emotional control, as had previously been observed in the results of the preliminary questionnaire.

Changes in neural activity and physiological status at the first pre-round period

Next, we examined how physiological states in the first pre-round period with the highest level of strategic decision (Figure 1C) changed in relation to the win or loss of a match. We recorded neural activity during pre-round periods in different situations during an FVG match. A mobile EEG was used to enable brain measurements of e-sport players in a real-world environment. We examined the neural oscillations associated with the match outcome by focusing on the frontal areas. In addition, we used an electrocardiogram (ECG) to determine effects of stress and an electromyogram (EMG) to investigate the effects of arm movement. Our analysis compared the physiological status in the first pre-round period of win and loss of a match. As a result of a cluster-based permutation test, we found that the amplitude of high-frequency gamma (55–76 Hz) oscillations, mainly in the left frontal area, increased in a winning match (Figure 2A: $p = 0.003$). The heart rate (HR) and root-mean-square (RMS) of the EMG did not differ significantly depending on win or loss as shown in Figure 2B: $t(38) = 0.35$, $p = 1.00$; Figure 2C, $t(38) = -0.006$, $p = 1.00$; and Figure 2D, $t(38) = 0.16$, $p = 1.00$. This result indicates that motion or motion-related artifacts did not induce the increase in neural oscillations before the round.

Changes in neural activity and physiological status at the third pre-round period

We examined how neural oscillations in the third pre-round period with the highest level of emotional control (Figure 1D) changed in relation to the win or loss of a match. We compared the physiological status in

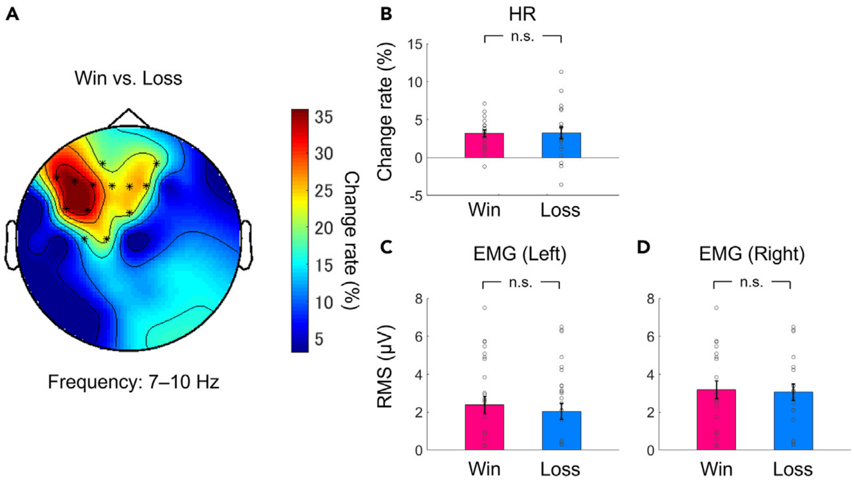

Figure 3. Changes in neural activity and physiological status at the third pre-round period

(A–D) Parameters during the third pre-round period with the highest success level of emotional control: the left panel shows topographic maps of differences in the amplitude of neural oscillations between winning and losing a match. A cluster-based permutation test was performed, and alpha (7–10 Hz) power of the frontal area significantly increased in the win condition (A). The heart rate (B) and left (C) and right (D) EMG did not significantly change between the win and loss conditions. Asterisks in the topographic map indicate clusters of channels that showed a significant increase. Error bars represent the standard error of the mean. Statistical significance is indicated at $^*p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$.

the third pre-round period of won and lost matches. As a result, we found that alpha (7–10 Hz) oscillations increased in the left frontal region in winning matches (Figure 3A: $p = 0.009$). The HR and EMG activity did not change for wins or losses as shown in Figure 3B: $t(38) = -0.069$, $p = 1.00$; Figure 3C, $t(38) = 0.56$, $p = 1.00$; and Figure 3D, $t(38) = 0.20$, $p = 1.00$. The HR showed a limited increase in both wins and losses, which could be attributed to social pressure and excitement. No immediate changes in the RMS of the EMG before the winning round indicated that the increase in neural oscillations before the round was not induced by motion or motion-related artifacts.

Correlation between the level of subjective indices and change in neural oscillations

At a specific pre-round period in a winning match, subjective indices and neural activity were found to increase. We focused on inter-participant variations and investigated whether a direct relationship between the subjective index and neural activity existed. We found a correlation between the level of strategic decision and the conditional difference of averaged frontal high-gamma power in the first pre-round period (Figure 4A: $r = 0.60$, $p = 0.005$). The correlation between the level of emotional control and the conditional difference in averaged frontal alpha power in the third pre-round period was also found to be significant (Figure 4B: $r = 0.59$, $p = 0.006$). In other words, participants who showed stronger subjective indexes had larger neural differences and vice versa.

Changes in neural activity and physiological status in all pre-round periods

To investigate the fluctuations in physiological status common to all pre-round periods unrelated to a particular situational change, EEG, HR, and EMG data were compared according to the win or loss status of each round. In pre-round periods of wins, an increased amplitude was found in the beta band (15–24 Hz) in the parietal brain area, including the left and right sensorimotor cortices (Figure S1a: $p = 0.005$). There were no conditional differences in the average HR and RMS of the EMG, as shown in Figure S1b: $t(38) = 0.12$, $p = 1.00$; Figure S1c: $t(38) = 0.19$, $p = 1.00$; and Figure S1d: $t(38) = 0.24$, $p = 1.00$. No immediate changes in the RMS of the EMG before the winning round indicated that the increase in neural oscillations before the round was not induced by motion or motion-related artifacts.

Changes in neural activity and physiological status in the round

To investigate the fluctuations in physiological status within the 44.9 ± 13.0-s round periods (mean ± SD) that involved actual visuomotor manipulation, EEG, HR, and EMG data were compared according to the

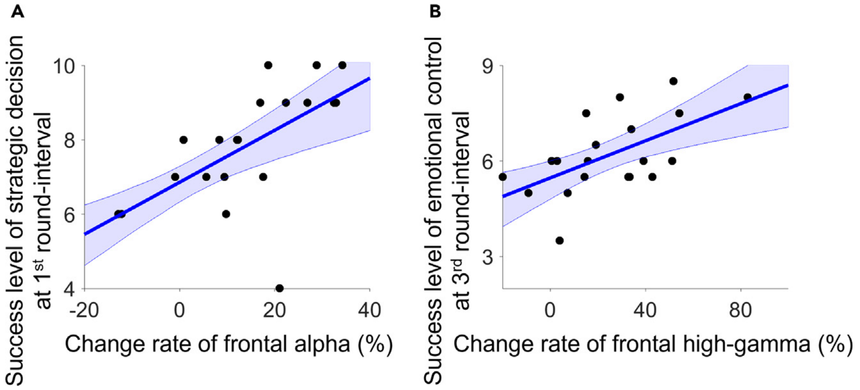

Figure 4. Correlation between the level of subjective indices and change in neural oscillations

(A and B) We computed the conditional difference in the change power rate of neural oscillations averaged over the bands and channels included in the significant clusters in the first and third pre-round periods, where the cluster-based permutation test confirmed significant differences. The success levels of emotional control in pre-round periods (4) and (5) were averaged as the subjective index in the third pre-round period. The correlation coefficients between mean power and the subjective index were calculated for all participants. We found a correlation between the level of strategic decision and averaged frontal high-gamma power in the first pre-round period (r = 0.60, p = 0.005) (A). The correlation between the level of emotional control and averaged frontal alpha power in the third pre-round period was also found to be significant (r = 0.59, p = 0.006) (B).

win or loss status of each round. The low-gamma (33–48 Hz) power in the right and left visual areas significantly increased in winning rounds (Figure S2a: p = 0.004). The difference in HR was not significant as shown in Figure S2b: $t(38) = 1.01$, p = 0.96. However, the RMS of the EMG increased in the case of winning rounds, as shown in Figure S2c: $t(38) = 8.47$, p<0.001, and Figure S2d, $t(38) = 7.64$, p<0.001.

Time-frequency analysis of frontal gamma oscillations at the first pre-round period, frontal alpha oscillations at the third pre-round period, and parietal beta oscillations at all pre-round periods

Based on the results shown in Figures 2A, 3A, and S1a, to determine at what time in the pre-round period significant changes in neural oscillations occurred, we calculated the differences in the multitaper spectra between the win and loss conditions from −8.0 s to 0.0 s from the start of the round and over a range from 1 Hz to 95 Hz Figure S4a represents the time-frequency distribution in the first pre-round period averaged over the channels that changed significantly in Figure 2A. As a result of a permutation + *Z*score test after FDR adjustment, high frequency gamma (58–76 Hz) activity in the first pre-round period was significantly changed from −6.2 s to −3.1 s (Figure S4b). Figure S4c represents the time-frequency distribution in the third pre-round period averaged over the channels that changed significantly in Figure 3A. Alpha (7–10 Hz) activity in the first pre-round period was significantly changed from −3.7 s to 0.0 s (Figure S4d). Figure S4e represents the time-frequency distribution in all pre-round periods averaged over the channels that changed significantly in Figure S2a. Beta (58–76 Hz) activity in all pre-round periods was significantly changed from −7.5 s to 0.0 s (Figure S4f).

DISCUSSION

The importance of strategic decisions and emotional control in e-sports has been reported in recent studies. For example, interacting with a spatial environment allows e-sport players to make sequential and dynamic decisions.[7] Considering the answers from an open-ended questionnaire, a common strategic decision among advanced FVG players is the evaluation of patterns of behavior that will be effective against their opponent, a few seconds before a round, to gain an advantage in the fight. Especially in the first pre-round period, a player needs to consider many strategic options based on the characteristics of a first-time opponent. The first or second round results help in ruling out any ineffective options, thereby limiting the options in the third pre-round period. Therefore, the later the pre-round period is, the lower the importance of the strategic decision. In contrast, e-sports bring intense competition and emotional experiences to the players.[8] A previous study analyzing the psychological state of e-sports and traditional sports athletes at the stage just before competition reported the emotional stress experienced by athletes (e.g.

fear of failure).[30] Players use a variety of approaches to self-care for positive and negative emotions. Previous studies examining the physiological status of skilled players in FVG matches suggest the point at which emotional control is most prominently required.[31] Their HR tended to increase in the final round compared with that in the first round. The increase in HR in the end phase of the match may signify great emotional change associated with the situation that directly determines a win or loss. These findings supported our results that a strategic decision is most important during the first pre-round period (Figure 1C), and conversely, emotional control is most important during the third pre-round period (Figure 1D). In a previous study on modern pentathlon, elite athletes were interviewed just before competition about their cognitive states and behaviors.[32] The majority of athletes consistently mentioned strategic decisions such as anticipation of tasks of the competition and rehearsing optimal execution, and emotional control, such as attempts to be detached from emotions and to focus on the technical things. These results are quite similar to the results obtained from the open-ended questionnaire in our study, and support the attribution of strategic decision and emotional control as the major cognitive activities of advanced players in the pre-round period.

Several studies that recorded neural activities non-invasively in both humans and non-human primates have shown a positive correlation between the blood oxygenation level-dependent signal and oscillatory power changes at high frequencies (30–150 Hz) arising from cortical areas.[33] Therefore, the increase in gamma power shown in Figure 2A is likely to roughly represent cortical activation. In the first pre-round period, the importance of a strategic decision regarding the optimization of the player's behavioral pattern is high because the information for the opponent's behavioral pattern is not yet obtained, whereas the importance of emotional control is relatively low because the win or loss of the first round is not directly related to the win or loss of the match. A previous study on a Japanese board game (Shogi), which, similar to e-sports, requires a high level of strategic decision ability, directly identified the brain regions responsible for strategic decisions.[14] The results of tracing brain activity in deciding whether an attack- or defense-oriented strategy is more appropriate in a given situation suggested that the dorsolateral prefrontal cortex is involved in strategic selection. According to the approximate correspondence between the EEG 10-10 system and the Brodmann area, the part (AF3, F3, F5) of the channels of the red area with particularly increased high frequency gamma power in Figure 2A encompasses the DLPFC. The strategic decision-making ability used in advanced intellectual board games may be functionally similar to that in e-sports. Furthermore, the system II of the neural proficiency hypothesis in optimal performance may be well applied in this situation.[11,12] The brain's resources may be intensively consumed in frontal regions to cope with unexpected events. The activation of the frontal cortex represents centralization.[9,10,13] In contrast to high frequencies, previous studies have shown a negative correlation between the blood oxygenation level-dependent signal and power changes at low frequencies (8–30 Hz) arising from cortical areas.[33] Therefore, an increase in alpha power in Figure 3A is likely to roughly represent cortical deactivation. In the third pre-round period, the task is automated as the strategy becomes defined owing to the experience of playing against the opponent. Activation of the frontal cortex is rather undesirable for tasks with low subjective difficulty.[11–13] Conversely, emotional control is most important, as a win or loss in the next round determines the outcome of the match. In this situation, neural information processing may be well suited to the transient hypofrontality framework.[15–17,22] The frontal region is temporarily inhibited with increased alpha-synchronization to optimize information processing and anxiety levels. A previous study revealed EEG recordings during cognitive reappraisal using unpleasant pictures suggested that the inactivation of DLPFC, accompanied by increased alpha oscillations, corresponds to spontaneous emotion regulation.[34] The part (F3, F5) of the channels of the red area with particularly increased alpha power in Figure 3A encompasses the DLPFC. A fundamental mechanism that suppresses unpleasant emotions may also be applied to emotional control in e-sports. For example, e-sport players may be subconsciously desensitized to emotional changes close to the important phase, making it easier to perform as usual.

We claimed that the suppression of negative emotion via alpha oscillations occurs in the period immediately before the third round and that this leads to success in the next round; however, this claim is questionable because the window of time between rounds is 8 s and starts immediately after the end of the previous round. The most memorable event at the end of the second round is thought to be a KO scene. For example, winning can bring a reward of achievement to the player, whereas losing can evoke a mental upset in the form of frustration and disappointment. Therefore, we focused only on matches that had a third round. We compared neural activity in the round-interval period immediately before the third round according to a win or loss of the second round. The results of the cluster-based permutation test showed that neural activity did not change significantly in all frequency bands including the alpha band and all brain regions (pvalues for all clusters were greater than 0.24). Thus, at least in this phase, it is unlikely that the latest win or loss results in any neural activity observable in the EEG. The increase in frontal alpha power just before the third round is a mental activity directly related to future information, not to impressive and immediately preceding information. This finding supports our contention that alpha activity is an emotional control for future performance enhancement and not a possible side effect of immediate past events.

Figures 4A and 4B show a more direct relationship between the subjective index and the amplitude of frontal neural oscillations. These findings suggest that in high-level e-sport matches requiring different types of mental and psychological states depending on the phases of the match, the performance of e-sport players is optimized through activation and deactivation of the frontal cortex.

Sensorimotor rhythms (SMR) are thought to reflect the suppression of somatosensory processing in the parietal cortex to maintain an optimized state for task processing efficiency.[13,20,35–38] The results in Figure S1a may indicate an increase in performance of automatic visuomotor action by sensory-motor rhythms in the pre-round period, independent of changes in the match situation. Although theta oscillations are important in optimizing the performance of single action,[20,23,39,40] theta oscillations did not change with win/loss in any pre-round period. It has been reported that an increase in theta activity indicates the involvement of working memory and motor control.[13,20] In the pre-round period without a visuomotor task as competition, the neural activity reflecting the above cognitive functions may not be directly related to the match results.

The results of the time-frequency analysis revealed that the frontal high frequency gamma, frontal alpha, and parietal beta fluctuations observed in the first pre-round, third pre-round, and all pre-round periods, respectively, occur at specific times during the pre-round period (Figures S4a–f). Frontal high frequency gamma activity associated with strategic decisions was localized relatively early (−6.2 s to −3.1 s) in the pre-round period. This gamma activity turned to a decline just before the start of the round, and the trend was maintained throughout the round, as observed in the frontal area shown in Figure S2a (the trend was also observed in the high frequency gamma band). According to interviews with participants, advanced FVG players concentrate especially on visuomotor action during the round. The results shown in Figures S2a, S4a, and S4b may represent a process of reallocation of brain resources that were originally focused on strategic decisions to visual processing (activation of visual area, shown in Figure S2a) during the round. In other words, players may need to cut off strategic decisions early in the pre-round period because of the time lag involved in such a bold cognitive state switch as described above. On the other hand, frontal alpha activity associated with emotional control was localized in the latter half of the pre-round period (−3.7 s–0.0 s). Because pressure and anxiety about winning or losing a match are thought to increase as the final round approaches, the need for emotional control might be particularly likely to increase around the start of the final round. Parietal beta activity was observed over almost the entire pre-round period (−7.5 s–0.0 s). Maintaining an idling state[13,20,35–38] for visuomotor activity from one round to the next via the SMR may be useful in a match consisting of multiple rounds.

Research on visual attention has revealed that neural activity in the gamma-band of the lower visual cortex is associated with the regulation of visual information processing.[41] The prominent performance of action video game players in visual discrimination tasks is accompanied by significant activation/deactivation of the visual cortex.[42] Figure S2a suggests that FVG players can gain an advantage during competitions by utilizing a superior visual attention system.

The increase in the RMS of the EMG in the winning round (Figures S2c and S2d) may reflect the number of the attack command inputs. In FVG, it is natural to assume that the winner has more chances to attack, which may increase the number of the attack command inputs. Therefore, we investigated the relationship between the number of attack command inputs and the win or loss of a round by a two-tailed paired *t*-test. The results showed that the number of times the button was pressed was not significantly different between the win and loss conditions as shown in Figure S3: $t(38) = -0.43$, $p = 0.67$. Thus, this increase in myoelectricity of the arms may be a result of the player optimizing motor control related to performance, rather than reflecting an action that the winner should perform in the game specification.

In this experiment, we adopted the match format as the task rather than the single-action format that has been used in previous studies.[39,43–46] The match and single-action formats differ significantly in two respects: uncertainty and timescale. In a single-action format, players are informed of the actions that they will perform in advance, and one person completes the series of task actions. However, in a match format, two or more players interfere with one another's actions. It is impossible to know the appropriate actions to take in advance because the actions of the players change completely depending on the actions of their opponents. In addition, in the case of single-action tasks, the action time is usually within 10 s. However, the playtime of the match format in this experiment spanned over 1 min. Beyond the perspective of formal differences in the task, this finding provides new insights into the role of neural oscillations in information processing for cognitive activities.

Owing to the short history of e-sports, coaching and training techniques are still being developed.[47,48] Recent previous studies have reported that a stressful environment increases the training efficiency of mechanical skills in e-sports players.[49] Although the literature on mindfulness meditation is abundant for traditional athletes,[50] few studies have analyzed e-sports athletes. In any case, in many e-sports genres, coaching has not been established in accordance with the actual game format. Practical guidelines on how to use strategic decision-making and emotional control depending on the phases of a match are not at all obvious for e-sports coaches or players, and no similar findings have been reported in the research field. This study implied that the emphasis on strategic decisions in the early stage of the match and on emotional control in the later stage of the match are directly related to winning or losing, and that the success or failure of their use is accompanied by frontal neural activities in specific bands. The finding that the success or failure of these psychological and mental activities are expressed as EEG biomarkers in specific bands and brain regions allows for the quantification of performance during the match based on the real-time physiological state of the player. Players play according to specific guidelines based on our findings, and are given feedback on the EEG information linked to the success or failure of their psychological and mental states. Furthermore, a combination of these techniques with the existing biofeedback system could help to establish a new training method for e-sports players. For example, using EEG-based neurofeedback[51,52] to enhance frontal gamma power before a match allows players to make strategic decisions in an ideal neuroactive state. These new methods are expected to improve the effectiveness and certainty of coaching. In addition, we established an effective approach for assessing the cognitive function of specialists in specific visuomotor tasks in a real-world environment. A future application of this approach to players and gameplay of other e-sport genres will further extend our understanding of the cognitive properties of strategic decision-making and emotional control; this should be an important topic for future research.

This study showed that specific cognitive activities in a pre-round period are associated with a win or loss in a match. Furthermore, neural fluctuations were suggested to reflect the success level in "strategic decision-making" and "emotional control," which are important mental and psychological activities in interpersonal competitions via a computer video game.

Limitations of the study

To provide an informed interpretation of our findings and to further clarify the link between FVG and physiological state, we highlight certain limitations of our measurement method.

The reference channel of the EEG device (eegosports; ANT Neuro b.v., Hengelo, Netherlands) used in this study was placed at AFz and CPz to improve robustness to noise, so no EEG data were measured in that channel. The absence of some data in the frontal and parietal regions can slightly affect the distribution of topographic maps and the results of the cluster-based permutation test. However, because AFz and CPz are located in the midline, it is highly unlikely that the absence of AFz and CPz is responsible for the left hemisphere bias of the frontal alpha/gamma power distribution in the winning condition.

HR normalization is based on ECG data for the period from 16 s to 8 s before the start of the match. Players experience a minute or more of rest between matches, but it is possible that they are under a certain amount of strain as the time until the next match decreases. Because heart rate is sensitive to stress responses, it is necessary to consider the possibility that baseline HR was affected.

In this study, 20 expert players played an FVG using an arcade controller. Seventeen participants gripped the lever with their entire left hand from the upper side, whereas the remaining three participants gripped the lever from the lower side between their fingers. Because a change in approach to holding the lever could decrease mechanical skill performance, the three players played the game in their usual way. It should be noted that this difference in grip type may affect the muscle output of the left hand during the round. All three participants who gripped from the lower side had greater RMS of EMG in their left arm on the win condition. This trend is consistent with the results shown in Figure S2c.

STAR★METHODS

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106845.

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AUTHOR CONTRIBUTIONS

S.M. designed the study; S.M. and K.W. performed the experiment; S.M. analyzed the data; S.M., N.S., and M.K. wrote the article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
eego™sports software	ANT Neuro	https://www.ant-neuro.com/products/eego_sports/eego-software
MATLAB 2019a	MathWorks	RRID:SCR_001622
FieldTrip	Donders Institute for Brain, Cognition and Behavior	RRID:SCR_004849
Street Fighter V Arcade Edition	Capcom	https://www.capcom.co.jp/sfv/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Sorato Minami (sorato.minami.yg@hco.ntt.co.jp).

Materials availability

This study did not generate new materials.

Data and code availability

- Data reported in this study cannot be deposited in a public repository because ethical restrictions apply to original data. To request access, contact Sorato Minami (sorato.minami.yg@hco.ntt.co.jp).
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND PARTICIPANT DETAILS

We recruited 20 expert FVG players (all men; mean age=24.4 years; range=18–35 years). All participants had league points higher than 35,000 (rank: Grand Master) in Street Fighter V Arcade Edition (Capcom Co., Ltd., Osaka, Japan), which ensured that they were highly proficient in the game. Athletes provided written informed consent for participation. Our study was approved by the Ethics and Safety Committees of NTT Communication Science Laboratories (protocol number H30–002). We followed the tenets of the Declaration of Helsinki.

METHOD DETAILS

Procedure

In an FVG, the player controls a playable character with an arcade controller and fights against an opponent in a virtual world. The players give direction commands through the joystick controller with the left hand to change the position of the virtual character and give attack commands through button presses with the right hand. The first player to reduce the opponent's life gauge to zero is the winner of the round. The match format was a two-round first-pass system. The participants regarded the result of each match as that of an independent competition. Each match was played online using a ranked match mode, in which players were frequently matched with players of a similar rank. The opponent was different for each match. There were six possible win/loss branching patterns within a single match (Figure 1A). The experiment was conducted over three separate days. In the experiment, on day 1, players were asked to repeat the match with an 8-s baseline period and more than 1-min rest period to reset their mental states. In addition, the players rested for 30 min after playing for 1.5 h. There were 403–530 matches in total. Each branching match pattern of all participants contained more than 50 trials. The round winning percentage was 66.3%–40.0%

(mean ± SD=53.0% ± 7.2%). The match-winning percentage was 64.7%–40.3% (mean ± SD=55.0% ± 7.4%). The match consisted of a repetition of the round period (from the disappearance of the word "Fight" until "KO" or "Perfect" appeared on the screen) and pre-round period (from the appearance of "KO" or "Perfect" until "Fight" disappeared from the screen). The pre-round period was defined as the 8-s period before the appearance of the "Fight" prompt. Players focused on the visuomotor actions during the round period. In contrast, the pre-round period was not accompanied by visuomotor actions. In the pre-round period, the visual representation was almost the same each time. Hence, the experimental conditions during this period were relatively controlled. In the pre-round period, players made psychological and mental activities for better performance in the next round. An 8-s complete rest period between the rest and the first pre-round period was defined as the baseline for each match.

EEG/ECG/EMG data acquisition

We simultaneously measured EEG, ECG, and EMG data. Using an EEG device (eego™sports; ANT Neuro b.v., Hengelo, Netherlands), neural oscillations were recorded. Using a Biopac MP150 (Biopac Systems, Inc., Goleta, CA, USA), the HR and electrical activities of the arm muscles were recorded. The sampling frequency was 2,000 Hz for all measurements. We used 63 silver chloride (Ag/AgCl) active electrodes during EEG recordings. The electrodes were placed on the scalp as per the 10-10 system (Fp1, Fp2, AF3, AF4, AF7, AF8, F1, F2, F3, F4, F5, F6, F7, F8, FC1, FC2, FC3, FC4, FC5, FC6, FT7, FT8, C1, C2, C3, C4, C5, C6, T7, T8, CP1, CP2, CP3, CP4, CP5, CP6, TP7, TP8, P1, P2, P3, P4, P5, P6, P7, P8, PO3, PO4, PO5, PO6, PO7, PO8, O1, O2, Fpz, Fz, FCz, Cz, Pz, POz, Oz, M1, and M2). EEG signals were referenced to AFz and re-referenced offline to CPz in the analysis phase. ECG measured the inter-beat intervals (R–R intervals). The electrodes were made of silver-silver chloride (Ag–AgCl). EMG measured the electrical activities produced by the skeletal muscles of the extensor digitorum of the right and left forearms that are responsible for joystick control and button press. The electrodes were made of Ag–AgCl. The EMG signals were referenced to the elbows.

QUANTIFICATION AND STATISTICAL ANALYSIS

We analyzed the measured data using the Fieldtrip toolbox[53] for MATLAB (MathWorks, Natick, MA, USA). Pre-round data with large head and body movement artifacts were removed using a fixed-point camera. Data with marked noise in the raw waveform in the round/pre-round periods were manually removed. Artifacts originating from blinks, EMG, or heart beats were removed using independent component analysis. Zero-padding on 8-s pre-round data to reach 10 s (2000×10 time points) and zero-padding on round data to reach 100 s (2000×100 time points, attributed to the round data being <100 s) were performed. Band-pass filtering between 1 and 95 Hz was then applied before fast Fourier transform analysis.

We detected peak signals in ECG data. The R–R intervals were resampled at 10 Hz through cubic spline interpolation. Hum noise at 50 Hz in the EMG were noted. Thus, a band-stop filter was applied to 47.5–52.5 Hz. We shifted a 2-s time window (2,000×2 time points) by 0.1 s and calculated the RMS. The R–R interval and RMS of the EMG were averaged for all periods. We normalized the EEG/ECG datasets as the rate of change from the baseline. The baseline comprised the match-interval data. For six branching patterns of one match, ECG/EMG datasets were averaged for all trials for each participant. We conducted a two-tailed paired *t*-test to compare the HR or RMS of the EMG in pre-round/round periods by the results (win or loss) of a match or round. All *p*-values were Bonferroni corrected; all *p*-values were multiplied by the number of combinations (3.0) of HR (1.0) and RMS of EMG (left/right=2.0). Significance was set at alpha=0.05.

Cluster-based permutation tests,[54] as implemented in Fieldtrip, were conducted with the null hypothesis that the dataset observed in the win and loss conditions for each branching pattern of one match is drawn from the same probability distribution. Spatial adjacency between channels was computed via a triangulation algorithm. A two-tailed paired *t*-test was conducted for a selected set of frequency bands (1–95 Hz, 1-Hz steps) or a selected set of 63 channels, and initial cluster forming thresholds at a value corresponding to $p<0.025$. This procedure was repeated 10,000 times. On simulation runs with a positive result, significant clusters were adopted.

Based on the results shown in Figures 2A, 3A, and S1a, to determine at what specific time during the pre-round period significant changes in neural oscillations occurred, the power at each time-frequency point was calculated using multitaper spectral analysis.[55] Two-second time windows were shifted at 100 ms intervals from −8.0 s to 0.0 s from the start of the round. Frequency was increased linearly from 1 Hz to 95 Hz using 1 Hz steps. Then, the difference in power between win and loss trials at each point on the time-frequency plane was calculated for each participant. The time-frequency data points in the first, third, and all pre-round periods were averaged over the channels that showed significant changes in Figures 2A, 3A, and S1a, respectively. A method called "permutation + *z*-score test"[56] was used for statistical analysis. Win and loss trials were randomly rearranged, and then the power difference was recalculated. This was repeated 1,000 times. The difference between the original dataset and the mean of all permutations was then expressed in units of standard deviation across all permutations. To combine the time-frequency maps of the *p*-values between participants, the *p*-values were converted to equivalent *z*-values using the inverse cumulative normal distribution function. The *z*-values were combined between participants and finally converted into probabilities. To correct for multiple comparisons, the distribution of *p*-value results was analyzed using a false discovery rate (FDR) procedure[57] and a *p*-threshold was calculated that set the expected rate of falsely rejected null hypothesis at 5%.

Questionnaire

Prior to this study, we conducted a preliminary questionnaire with 15 advanced players (all men; mean age=30.6 years; range=18–43 years), asking an open-ended question ("Please describe your cognitive state or usual behavior during the pre-round period"). The results of the questionnaire, taken as a whole, were organized into two cognitive activities as strategic decision and emotional control. Strategic decision common to skilled players is an attempt to decide their actions during the next round in advance. Skilled players infer the most effective pattern of action (e.g., combination moves and counterattacks) in the pre-round from the characteristics of the opponent. Emotional control common to skilled players is an attempt to suppress the mental agitation (anxiety of losing) that arises from pressure at critical junctures of the match. By consciously suppressing negative emotions before the round, the players can perform as usual during the round. In interviews conducted with participants after the preliminary questionnaire, it was confirmed whether the above definitions of strategic decision making and emotional control were common views among advanced players, and all participants agreed. Given the results that strategic decision and emotional control are attributed to the main cognitive states in the pre-round period, subjective quantification was conducted using a questionnaire. The leading questionnaire is to ascertain the presence of commonality in the success level of strategic decision and emotional control of skilled players depending on the phase of the match. Based on their experiences of all matches during the experiment, players answered a subjectively averaged degree to which the aforementioned strategic decision or emotional control had been successful in the five possible pre-round periods (Figure 1B). For example, players were asked the question, "During the pre-round period between the second and third rounds, did you feel that you were successful in making strategic decisions and controlling your emotions? Please answer with a number from 1 to 10." The level in a winning match compared to that of a losing match was scaled from 1 to 10 wherein, compared to the losing case, 1, 5, and 10 represented the same, moderately better, and much better levels, respectively. Because all participants in the preliminary experiment stated that the success level of strategic decision or emotional control was always lower in the losing case than that in the winning case, we omitted ranges below 1 in this questionnaire. Players completed the leading questionnaire only once after all matches in the current experiment. An open-ended question ("Please describe your cognitive state or usual behavior during the pre-round period") was also asked after the current experiment, immediately before the above leading question. Normality and equivariance between the pre-round period conditions for the results of the strategic decision and emotional control questionnaires were checked using the Shapiro–Wilk test[58] and the Levene test,[59] respectively. Conditional differences in the success degree of strategic decision and emotional control at the five possible pre-round periods within a single match were assessed with a one-way repeated-measures ANOVA. Two-tailed paired *t*-tests were conducted between each pair of the five pre-round periods (Figure 1B). The *p*-values were Bonferroni corrected; all *p*-values were multiplied by the number of combinations (10.0) for each subjective index. Significance was set at alpha=0.05.

Correlation

We examined the presence of a correlation between subjective measures and neural activities by focusing on the variability among participants. The conditional differences in the change power rate of neural oscillations over the bands and channels included in the significant clusters in the first/third pre-round periods were averaged, where the cluster-based permutation test confirmed significant differences. The success levels of emotional control in pre-round periods (4) and (5) were averaged as the subjective index in the third pre-round period. Correlation coefficients between mean power and the subjective index in the first/third pre-round period were calculated for all participants, respectively. Significance was set at alpha=0.05.