The Effect of Pedaling At Different Cadence On Attentional Resources

Mayu Akaiwa

Sapporo Medical University

Koki Iwata

Kashiwaba Neurosurgical Hospital

Hidekazu Saito

Sapporo Medical University

Eriko Shibata

Hokkaido Bunkyo University

Takeshi Sasaki

Sapporo Medical University

Kazuhiro Sugawara (✉ kaz.sugawara@sapmed.ac.jp)

Sapporo Medical University

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Abstract

Research aim: We investigated the relationship between attentional resources and pedaling cadence using electroencephalography (EEG) to measure P300 amplitudes and latencies.

Methods: Twenty-five healthy volunteers performed the oddball task while pedaling on a stationary bike or relaxing (no pedaling). We set them four conditions: 1) performing only the oddball task (control), 2) performing the oddball task while pedaling at optimal cadence (optimal), 3) performing the oddball task while pedaling faster than optimal cadence (fast), and 4) performing the oddball task while pedaling slower than optimal cadence (slow).

Results: P300 amplitudes at Cz and Pz electrodes under optimal, fast, and slow conditions were significantly lower than that under control conditions. P300 amplitudes at Pz under fast and slow conditions were significantly lower than that under the optimal condition. No significant changes in P300 latency at any electrode were observed under any condition.

Conclusion: Our findings revealed that pedaling at non-optimal cadence results in less attention being paid to external stimuli compared with pedaling at optimal cadence.

Introduction

Humans experience situations that require the execution of multiple tasks simultaneously. Dual tasks, where individuals perform two tasks simultaneously, degrade performance [1, 2]. Especially, simultaneous performance of a cognitive and a motor task is relevant in daily life. A good example includes using a smartphone while walking or driving. They increase the risk of falls and traffic accidents [3]. Performance degrading was suggested to be linked to attention [1]. "Attention" refers to a variety of hypothetical constructs by which the nervous system apprehends and organizes sensory input and generates coordinated behavior [4]. Attentional resources are defined as the amount of attention available to perform motor or cognitive tasks. When humans simultaneously perform two or more tasks, resources will be shared among tasks. Attentional resources, however, are limited in capacity, and simultaneous performance of two tasks causes a competition for attentional resources [5]. Therefore, simultaneous performance of a cognitive and a motor task results in deterioration of performance in one or both tasks.

In previous studies, participants were imposed a dual task, namely cognitive task and alternate leg movement. Performing cognitive tasks during walking reduced not only gait parameters but also cognitive ability [1]. Notably, a study suggested that gait in old healthy adults was affected more by concurrent cognitive tasks compared with that in young adults [2]. Y Lajoie, DA Jehu, N Richer and Y Tran [6] examined attentional requirements of walking at various speeds and reported that slow walking demonstrated significantly longer reaction time (RT) than preferred and fast walking speeds; walking at a preferred pace also led to longer RTs than did walking at a fast pace. These results indicate that slow walking speeds required more attentional resources than fast walking. However, this relationship between gait speed and attentional resources is debatable because these previous studies reported the behavioral

change but not neurophysiological assessments. Therefore, we investigate whether attentional resources are related to cadence of a locomotor task using electroencephalography (EEG).

In our study, to clarify attentional resources during alternating movement of lower limbs as a function of gait speed, participants were asked to perform oddball tasks while pedaling on a stationary bike. Pedaling has three advantages. First, the trunk and head of the participant are stabilized during pedaling compared to walking. Second, the pedaling device is light and portable. Third, studies investigating characteristics of brain activity reported that EEG can be performed during pedaling [7-9]. Therefore, we used pedaling in this study.

P300, an event related potential (ERP) component, is suited well to testing attention. Studies have reported that the P300 peak amplitude is proportional to attentional resources devoted to a given task and latency reflects stimulus evaluation time [10-12]. Moreover, P300 can be observed most clearly in an “oddball” task [10]. In the oddball task, participants are presented two categories of stimuli in random sequence, a rare (target stimulus) and a frequent (standard stimulus) stimulus. Also, there were few studies using a tactile oddball paradigm because cognitive-motor dual task were performed by auditory or visual oddball task [8, 13]. In this study, a tactile oddball design was adapted. Hence, we assessed the relationship between attentional resources and pedaling cadence by measuring P300 amplitude and latency.

On the other hand, previous studies reported that P300 amplitude is affected by loading of an ergometer and muscle activity increases with loading of the ergometer[8, 14]. Therefore, we also measured EMG during pedaling because there was a possibility that P300 amplitude is modulated by muscle activity.

We hypothesized that the P300 amplitude would increase and latency would be earlier at high cadence, whereas amplitude would decrease and latency would be slower at low cadence.

Materials And Methods

Participants

We determined the minimum sample size of the present study with G*power software from partial η -squared. This η -squared value was determined by the previous study [8]. The effect size was set at 0.29. With this analysis the minimum sample size was 18. We recruited 25 healthy young adults (age [mean $\pm$ standard deviation]: 22.80 $\pm$ 2.08 years; 18 males, 7 females), all of whom provided written informed consent. The study conformed to the Declaration of Helsinki and the Code of Ethics of the World Medical Association and was approved by the ethics committee of Sapporo Medical University (No. 1-2-62).

Stimulation

Electrical stimuli were randomly presented to the right index and fifth finger for 0.2 ms through ring electrodes attached to the first (anode) and second (cathode) interphalangeal joints. The index finger was stimulated for the target stimulus and the fifth finger for the standard stimulus. Stimulus intensity

was adjusted to three times the participant's sensory threshold [15]. Stimuli were presented at a constant 1000 ms interstimulus interval (ISI). Target and standard stimuli were randomly presented to 50% each [16]. It is because that the subjects would be fatigue by pedaling task and, moreover, it is necessary to as much signal averaging which evokes P300 as possible.

Experimental procedure

All participants performed the oddball task during either pedaling on a stationary bike or relaxing (no pedaling), and EEG was recorded. Participants were asked to perform two tasks, namely motor and count tasks. In the motor task, participants were instructed to pedal on a stationary bike at optimal cadence, 30% faster than optimal cadence, and 30% slower than optimal cadence. We decided the optimal cadence as they can perform comfortably pedaling. Participants were trained to maintain a smooth consistent pedaling cadence in synchrony with a metronome before recording EEG. In the count task, participants silently counted the number of target stimuli presented to their index finger on the stationary bike. We set them four conditions: 1) performing only the count task (control), 2) performing the count task during pedaling at optimal cadence (optimal), 3) performing the count task while pedaling faster than optimal cadence (fast), and 4) performing the count task during pedaling slower than optimal cadence (slow). One run varied randomly between 80 and 120 epochs (mean: 100 epochs) so the participants could not estimate the number of target stimuli. All participants performed three runs at each condition (300 epochs in total). The order of these tasks was randomized for each run. Participants had time to recover between runs. We used the modified Borg scale to measure participants' perceived intensity of physical activity. We recorded the rating of perceived exertion before and after each run. Before the recording session was started, all participants practiced motor tasks until they felt comfortable.

Recording and analysis

Using Neuropack system (Nihon Kohden, Tokyo, Japan), PowerLab and LabChart software (ADInstruments, NEW ZEALAND), EEG and EMG signals were digitized and recorded. A study reported that P300 amplitudes are observed better on the midline, especially Pz [17]. Electroencephalography (EEG) was performed by using Ag/AgCl electrodes placed over three scalp sites—Fz, Cz, and Pz—according to the International 10-20 system. Each scalp electrode was referenced to linked earlobes (A1A2). Electrode impedance was maintained below 5 k Ω at all recording sites. The electrooculogram (EOG) was recorded from the right suborbital region. Trials in which the EOG waveform exceeded 80 μ V were rejected [15]. Subsequently, we removed noisy epochs identified using a threshold of ± 200 μ V for other non-ocular artifact [13]. EEG signals were recorded with band-pass filter 0.1–300 Hz at a sampling rate of 1000 Hz and analyzed with low-pass filtering at 100 Hz. We only analyzed the waveform evoked by target stimulus. Analysis period of ERPs ranged from 100 ms before to 500 ms after stimulus onset. The 100 ms period before stimulus onset was used as baseline. P300 amplitudes were measured from baseline to peak. Peak amplitudes and latencies of P300 were measured at 250–500 ms [18, 19].

Electromyogram (EMG) was measured using a pair of Ag/AgCl electrodes (Blue-sensor NF-00; Ambu, Denmark) mounted over the right vastus medialis (VM) and the short head of biceps femoris (BF). EMG signals (DL-140; 4 assist, Japan) were sampled at 1000 Hz (Power Lab; AD Instruments) and band-pass filtered at 1–300 Hz. Then, full wave rectification and smoothing was performed. The values of moving window were 501 ms. EMG signals were normalized to maximum voluntary contractions. The averages of normalized EMG values over three pedal cycles were calculated. Figure 1 shows waveforms of acceleration, rectified EMG, and smoothed EMG at each condition in a typical participant. We assessed error rate using the following formula: Error rate = $(1 - \text{reported count} / \text{correct count}) \times 100$.

Statistical analyses were performed using the IBM SPSS 25 software (IBM Corp., New York, USA), and all data were expressed as the mean $\pm$ SD. The Shapiro–Wilk test was used to assess normality. To analyze the assumption of sphericity prior to repeated measures ANOVA, Mauchly's test of sphericity was used; if the result of the test was significant, indicating that the sphericity assumption was violated, the Greenhouse–Geisser adjustment was used to correct for this violation. Then, repeated measures ANOVAs were performed to determine the effect of CONDITION (control, optimal, fast, and slow) on P300 amplitude, latency, EMG, error rate, and physical activity intensity. Post-hoc tests were performed for significant differences in ANOVAs, with the Bonferroni correction for multiple comparisons. In addition, we analyzed bivariate correlations between P300 amplitudes and EMG activities. Significance was set at $p < 0.05$.

Results

Optimal, fast, and slow cadence were 51.56 ± 9.67 , 65.76 ± 13.99 , 35.88 ± 7.11 rpm, respectively. The Shapiro-Wilk test confirmed that all data, except physical activity intensity and %EMG, were normally distributed.

P300

Figure 2 shows grand-averaged ERP waveforms for all participants. The average of more than 100 recordings was obtained during each condition for all participants. Repeated measures ANOVA were used to assess the effects of cadence. There were significant main effects of CONDITION on P300 amplitude [Fz, $F(3,22) = 4.047$, $p = 0.011$; Cz, $F(3, 22) = 21.057$, $p < 0.001$; Pz, $F(3,22) = 16.551$, $p < 0.001$] but not P300 latency (Figure 3; Fz, $p = 0.900$; Cz, $p = 0.824$; Pz, $p = 0.698$). Post-hoc tests revealed that P300 amplitude at Fz decreased under fast and slow conditions compared to that under the control condition (control, 10.92 ± 5.18 μ V; fast, 8.62 ± 6.29 μ V; slow, 8.32 ± 6.14 μ V; control vs. fast, $p = 0.041$; control vs. slow, $p = 0.015$). P300 amplitude at Cz decreased under optimal, fast, and slow conditions compared to that under the control condition (control, 13.20 ± 4.30 μ V; optimal, 10.23 ± 3.87 μ V; fast, 8.82 ± 4.10 μ V; and slow, 8.32 ± 4.43 μ V; control vs. fast, $p < 0.001$; control vs. optimal, $p < 0.001$; control vs. slow, $p < 0.001$) and under the slow condition compared to that under the optimal condition ($p = 0.037$). P300 amplitude at Pz decreased under optimal, fast, and slow conditions compared to that under the control condition (control, 11.04 ± 4.14 μ V; optimal, 8.54 ± 3.55 μ V; fast, 7.49 ± 3.57 μ V; and slow, 6.96 ± 2.76 μ V;

control vs. fast, $p < 0.001$; control vs. optimal, $p < 0.001$; control vs. slow, $p < 0.001$) and under fast and slow conditions compared to that under the optimal condition (optimal vs. fast, $p = 0.044$; optimal vs. slow, $p = 0.030$).

EMG

Figure 4 shows %EMG of VM and BF. The Friedman test revealed a significant difference in %EMG of VM and BF due to conditions (VM, $p < 0.001$; BF, $p = 0.005$). Post-hoc analysis showed that EMG activity in VM increased under the fast condition compared to that under slow and optimal conditions (fast vs. optimal, $p = 0.008$; fast vs. slow, $p < 0.001$) and under the optimal condition compared to that under the slow condition (optimal vs. slow, $p = 0.018$). When the relationship between P300 amplitude and %EMG was analyzed by Spearman's rank correlation test, no significant correlation under any condition was observed (Figure 5).

Error rate and intensity of physical activity

Figure 6 shows the error rate and Table 1 shows the intensity of physical activity. There were significant main effects of CONDITION on the error rate. [$F(3, 22) = 5.020$, $p = 0.003$]. Post-hoc analysis showed that the error rate increased under the slow condition compared to that under the control condition ($p = 0.005$). Intensities of physical activity were not significantly different under any condition.

Discussion

The results showed that 1) P300 amplitudes decreased under optimal, fast and slow conditions relative to the control condition at Cz and Pz, 2) P300 amplitudes decreased under fast and slow conditions compared to that under the optimal condition at Pz, and 3) P300 amplitudes were not significantly different between fast and slow conditions at Fz, Cz, and Pz. Our results showed that the optimal cadence is slow compared to previous studies[20]. It could be because the participants performed pedaling on the stationary bike like a bicycle in previous studies, while performed on the reclining chair in present study.

Studies have reported that P300 amplitude is proportional to the amount of attentional resources devoted to a given task [10, 12] and decreases in more difficult tasks, such as dual tasks compared to a single task [21]. MA Just, PA Carpenter, TA Keller, L Emery, H Zajac and KR Thulborn [22] reported that brain activation distributes between two tasks in dual tasks. Our results suggested that attentional resources, which were shared between pedaling and counting, contributed to the reduction in P300 amplitude.

By contrast, P300 amplitude at Pz under fast and slow conditions decreased compared to that under the optimal condition. A study suggested that pedaling at optimal cadence may be a good reflection of movement frequency output generated by the central pattern generator (CPG) [23]. CPG, which is composed of spinal interneuronal networks, is a major component of the rhythm generating system [24, 25]. Both descending supraspinal drive and sensory feedback assist in fine tuning the output from central

pattern generators [24, 25]. Moreover, studies have reported that the activation of frontal and parietal lobes increased when the count task was performed [26, 27]. Sensory input during the count task may be integrated at frontal and parietal lobes through the peripheral nerve, spinal cord, thalamus, and primary somatosensory cortex. Pedaling at optimal cadence may demand a greater contribution of CPG, thus motor control at the cerebral cortex declines. Our results showed that attentional resources for the count task decreased under fast and slow conditions possibly because motor control increased at the cerebral cortex. Therefore, pedaling at non-optimal cadence demanded greater attentional resources than at optimal cadence, and attentional resources allocated to external stimuli decreased. However, it is our limitation that the slow or fast condition could be not only a dual task, but a multi task situation, i.e. motor activity, controlling the pace, counting the targets.

In this study, P300 amplitudes at all electrodes were not significantly different between fast and slow conditions. We hypothesized that P300 amplitude increased under the fast condition and decreased under the slow condition [6]. In that study, the participants performed reaction time tasks with auditory stimuli. Their results showed that compared to slow and self-selected speeds, accelerated walking generated faster RTs. The slowing of gait has been shown to result in greater lateral instability, increased attentional cost, reduced trunk smoothness, increased stride time variability, altered muscular activity, and higher energy costs, suggesting that slow walking increases equilibrium demands and decreases energy efficiency [28]. Thus, attentional resources during walking is decided by levels of posture control because gait speeds and posture control have a close relationship. However, in this study, participants performed alternating movement of the lower limbs on the reclining chair; therefore, the factor of posture control may be removed. For the reasons, a difference between the hypothesis and results may occur, irrespective of whether the task demands posture control.

Our results revealed that EMG activities in the VM and BF increased under the fast condition compared to slow and optimal conditions. A study reported that the value of EMG is decided by the activation of the primary motor cortex [29], and P300 amplitudes decrease with increasing activation of the primary motor cortex [30]. We suggested that a decrease in P300 amplitudes under the fast condition was caused by the increased activation of the motor cortex during pedaling at high cadence.

The error rate of the slow condition was the highest, thus slow conditions may be the most difficult tasks. A study revealed that executing smooth rhythmic motions very slowly is challenging for humans [31]. Similarly, it may be difficult to perform pedaling at a low cadence. This could suggest that the slow condition was a more complex task than optimal and fast conditions, thus pedaling at low cadence results in less attention being paid to external stimuli compared with pedaling at optimal cadence.

In this study, no significant changes in P300 latency were observed under any condition. Studies have reported that P300 latency is related to stimulus evaluation [11]. T Kida, Y Nishihira, A Hatta, T Wasaka, H Nakata, M Sakamoto and T Nakajima [19] showed that P300 latency measured during ignoring stimulus task, counting task, or reaction task is not different. Therefore, it is perhaps P300 latency was not affected by characteristics of tasks, such as pedaling at different cadence. Our results showed that no

significant correlation between P300 amplitudes and EMG activities existed under any condition. Thus, in this study, P300 amplitude and muscle activation may be independent.

Limitation

This study has several limitations. First, this study has not considered the effect of arousal. P300 amplitude is associated with arousal [32]. While, it is possible that pedaling cadence is associated with arousal, which is thought to expand the availability of attentional resources. Thus, it is possible that any relationship between pedaling cadence and P300 amplitude is due to changes in arousal. Second, our results, the P300 amplitude, would not be reflected the oddball response but instead processes related to counting and memory updating. The present study was adopted the count task, participants counted the number of target stimuli, but this task would appear to rely on working memory (i.e., holding the current count in one's mind and updating it).

Conclusion

This study assessed the relationship between cadence of alternating movement of lower limbs and attentional resources. Our findings indicated that pedaling at non-optimal cadence results in less attention being paid to external stimuli compared with pedaling at optimal cadence.

Abbreviations

EEG, Electroencephalography; RT, Reaction time; ERP, Event related potential; ISI, Interstimulus interval; EOG, Electrooculogram; EMG, Electromyogram; VM, Vastus medialis; BF, Biceps femoris; SD, Standard deviation; ANOVA, Analysis of variance; CPG, Central pattern generator; ACC, acceleration

Declarations

Ethics approval and consent to participate

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (Sapporo Medical University (No. 1-2-62) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

Consent for publication

Not applicable

Availability of data and materials

The datasets generated and analyzed during the present study are available from the corresponding author on reasonable request.

Competing interests

Not applicable

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Authors' contributions

All authors contributed to the study conception and design. Material preparation and data collection were performed by Mayu Akaiwa, Kazuhiro Sugawara and Hidekazu Saito. Formal analysis was performed by Mayu Akaiwa, Koki Iwata and Takeshi Sasaki. The first draft of the manuscript was written by Mayu Akaiwa and the review and editing of the manuscript were written by Kazuhiro Sugawara. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Table

Table 1: Rating of perceived exertion under each condition.

Modified Borg scale		
	Median	Range
control	0	0-0.5
fast	0	0-2
slow	0	0-1
optimal	0	0-1

Figures

Figure 1

Waveforms of acceleration (ACC), rectified Electromyogram (EMG), and smoothed EMG. The thin line shows the baseline (0 mV) of smoothed EMG

Figure 2

Grand-averaged waveforms at three cortical electrodes under each condition.

Figure 3

The amplitude and latency of P300 at each condition. Asterisks indicate significant differences ($p < 0.05$).

Figure 4

The %EMG of the right vastus medialis (VM) and the short head of biceps femoris (BF). Asterisks indicate significant differences ($p < 0.05$).

Figure 5

Correlations between conditions and P300 amplitude at each electrode. No significant correlations were found under all conditions.

Figure 6

The error rate of each condition. Asterisks indicate significant differences ($p < 0.05$).