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Research Article

The Effects of Aerobic Exercise on Eye Movement and Prefrontal Lobe Activation during Reading

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Abstract

Background: The purpose of this study is to present the optimal exercise intensity to help improve cognitive and reading skills by observing changes in eye movement and activation of the prefrontal lobe during reading after aerobic exercise with different intensities. **Methods:** 12 healthy adults were selected as subjects, and low and moderate intensity exercise were applied. Low intensity exercise was set to 40% HRmax, moderate intensity exercise was set to 60% HRmax, and exercise was performed for 20 minutes. During reading before and after exercise, eye movement and prefrontal lobe activation were measured. Two-way repeated measured ANOVA was conducted to analyse the differences in group, pre and post measurement in eye movement and prefrontal lobe activation. **Results:** Fixation number (p=.035) and Fixation time (p=.029) had a significantly interaction effect. Both low and moderate intensity exercises activated the prefrontal lobe on the left and right sides, especially in the right prefrontal lobe. **Conclusion:** Low intensity exercise was found to activate the prefrontal lobe more than moderate intensity exercise. If a low intensity exercise set to 40% HRmax is performed for 20 minutes before reading, it will help to improve cognitive function and reading ability of healthy adults to some extent during reading by activating eye movement and prefrontal lobe.

Keywords: Exercise; Eye movement; fNIRS; Prefrontal lobe; Cognitive function; Reading

Introduction

Reading a text to interpret the meaning of a given text and integrate the meaning to understand the content requires not only linguistic skills (such as phonology, meaning, syntax, and speech), but also general cognitive skills (such as working memory and execution control) [1]. One study has reported` that cognitive processing skills and sentence reading skills of mentally retarded students can be improved through cognitive function training, indicating that cognitive function is related to reading [2]. Therefore, studying brain science associated with reading is important considering that reading is an intellectual work done in the brain [3].

Cognitive is mental function of gathering and processing information to perform a task, including accepting, storing, and using various external information involving attention, memory, and problem-solving skills. Exercise psychologists are conducting studies in various ways, paying attention to relationships of these cognitive functions with exercise. Woo [4] has reported that cognitive function can be improved through light aerobic exercise or physical activity, and the higher the aerobic ability, the higher the degree of cognitive function improvement. Samani & Heath [5] have performed an experiment involving adults, including 14 in the experimental group who performed aerobic exercise at a maximum heart rate of 60 to 85% for 10 minutes and 6 in the control group who performed reading for 10 minutes. As a result of measuring reaction time of gaze movement through eye tracking tests before and after each group's experiment, the experimental group, which performed aerobic exercise for 10 minutes, responded faster and more accurately than the control group. And the reaction time of gaze movement improved by about 30 ms compared to before the exercise. They reported that concentration and cognitive ability were improved by about 14%, and brain function could be improved through aerobic exercise performed for 10 minutes. As such, results of previous studies have shown that exercise, even acute exercise, can improve brain function and cognitive function.

It has been reported that exercise can improve cognitive function by changing the brain structurally and functionally by creating brain neurons and blood vessels, increasing brain growth factors and neurotransmitters, and promoting synaptic connections [6,7]. An increase in cerebral blood flow means an increase in cerebral oxygenation, which reflects activation of brain function and improvement of cognitive function [8-10]. However, effects of exercise on cognitive function and brain blood flow can vary depending on age and exercise type. Previous studies have shown consistent improvement in cognitive function after acute aerobic exercise in children and the elderly [11,12].

However, whether exercise could improve cognitive function in young adults remains unclear [13,14]. Kang et al. [15] has reported that oxygenation levels of cerebral tissues are increased in young adults after performing an acute moderate intensity aerobic exercise and that an increase in blood flow in the prefrontal lobe is partially involved in improving cognitive function. Yanagisawa et al. [16] have reported that an acute moderate intensity exercise can in-crease the activity of the left dorsal prefrontal cortex while significantly improving cognitive function. Meanwhile, Rooks et al. [17] have reported that oxygenated hemoglobin and blood flow of the prefrontal lobe are increased during submaximal exercise but decreased during a vigorous-intensity exercise to the point of exhaustion.

Similarly, Subudhi et al. [18] have reported that a vigorous-intensity exercise that causes fatigue can decrease cerebral oxygenated hemoglobin concentration and brain function. As such, various contents have been reported for various age groups such as the elderly, adults, and children as to whether exercise and physical activities could improve cognitive function. Results of previous studies have indicated that exercise can improve cognitive function by increasing blood flow in the prefrontal lobe and positively affect reading ability and that it is important to set exercise intensity considering individual age and physical fitness.

On the other hand, to effectively perform exercise, it is necessary to appropriately set exercise program components such as intensity and frequency according to the exercise goal. In general, when planning an aerobic exercise, exercise intensity is set by physiological factors such as heart rate **(HR)** or maximum oxygen intake (VO2max). When planning muscle exercise, exercise intensity is set through maximum muscle strength **(1RM).** This exercise intensity is set differently according to an individual's physical state and goal. Accordingly, exercise duration and effect may vary. Therefore, it is possible to perform safe and efficient exercise only by setting the exact target of exercise and configuring the appropriate intensity, time, and frequency accordingly. However, most studies observing activation of the frontal lobe through exercise or change in eye movement have been performed through walking or light exercise, whereas studies on differences and changes according to various exercise intensity are insufficient.

Therefore, the aim of this study was to measure activation of the prefrontal lobe and eye movement when reading using fNIRS (**functional near-infrared spectroscopy**) and eye tracker after applying various intensities of exercise. fNIRS is an analysis method that checks the degree of brain activation by measuring changes in brain blood flow. It is useful for observing changes in the prefrontal lobe when performing cognitive tasks [19]. The cerebral cortex is the backbone of human cognitive operation located on the surface of the cerebrum. It is divided into the frontal lobe, parietal lobe, temporal lobe, and occipital lobe. Among them, the frontal lobe is in the front of the cerebrum. It is involved in rational thinking and judgment, abstract thinking, and emotional control [20]. Previous studies using fNIRS have reported that exercise is involved in the improvement of prefrontal activation and cognitive function by increasing cerebral blood flow and concentration of oxygenated hemoglobin [9,17].

Another measurement device, eye tracking, tracks the movement of the gaze by following the movement of the pupil. It is used in various fields such as medicine, sports, marketing, and design. In pedagogy and psychology, it has been mainly used in areas such as cognitive information processing, visual function, concentration and rapid reading, and special education. Recently, research studies on reading using gaze tracking equipment have mainly dealt with topics such as visual function, concentration, and rapid reading. While reading, the eyeball alternates between a fast-moving saccade and a slight-moving fixation. The movement of the eyeball varies depending on the difficulty of the text. In previous studies, the higher the difficulty of the text, the longer the average fixation time of the gaze, and the shorter the leap distance [21]. In other words, the reading speed decreases when reading a text with high difficulty due to difference between fixation time and leap distance. Reading speed increases when reading a text with a low difficulty. This shows that eye movement is closely linked to whether cognitive function is activated during reading.

Results of previous studies suggest that exercise can improve cognitive function when reading, which can be confirmed through the degree of activation of the prefrontal lobe and eye movement tracking. However, research on difference in cognitive function activation according to exercise intensity is insufficient. Thus, the aim of this study was to determine effects of exercise on cognitive and reading functions by observing the degree of prefrontal lobe activation and eye movement when reading articles.

Methods

Participant

In this study, 12 healthy adults who did not have clinical or musculoskeletal dysfunction without difficulty in reading Korean were selected as subjects. The purpose and procedure of this study were fully explained to all subjects. Only those who voluntarily signed the consent to participate in this study were enrolled as study participants. General characteristics of subjects who participated in this study is shown in Table 1.

Age	Weight	BMI	Rest HR	HRmax	40% THR	60%THR
(yrs)	(kg)		(bpm)	(bpm)	(bpm)	(bpm)
23.75±3.60	72.36±13.10	23.60±3.91	80.00±17.80	196.25±3.60	127.50±10.60	149.75±7.11

Data are presented as Means ± SD.
HR: Heart Rate; HRmax: Heart Rate maximum; THR: Target Heart Rate.

Table 1: General characteristics of study subjects (n=12).

Exercise Program

Exercise was performed using a fixed indoor bicycle. ACSM (**American College of Sports Medicine**) recommends that the target heart rate for low intensity exercise is 30% to 40% and the target heart rate for moderate intensity is 40% to 60%. Considering these recommended guidelines of ACSM and subjects of this study (i.e., healthy adults in their 20s and 30s), the exercise intensity was finally set at a low intensity and a moderate intensity to have target heart rates of 40% and 60%, respectively. To avoid interference effect of exercise as much as possible, experiments according to exercise intensity were conducted every two weeks. Heart rate at rest before the start of an exercise was measured. Based on this, the target heart rate was calculated using the Karvonen formula. Change in heart rate was observed in real time through a heart rate measuring device during exercise. Pedal load was adjusted to maintain the set target heart rate. The heart rate was gradually increased through a warm-up exercise for 5 minutes in the cycle. When the target heart rate was reached, the main exercise was performed for 20 minutes while maintaining the heart rate.

Eye Movement Measures

The gaze tracking device measured movement of the gaze using Tobii Pro Nano, a device that could track eye movement with data obtained by reflecting infrared rays on the cornea and provide empirical data on eye movement such as gaze fixing time and gaze fixing position while the subject performed the task. The gaze tracking equipment was installed on a 27-inch monitor. The subject was located 60-70 cm away from the monitor. Before reading the text, the subject sat in front of the monitor and performed pupil calibration on nine points through the gaze tracking device. The subject then performed text reading according to the prepared signal. Eye movements of the subjects upon reading were measured and recorded using Tobii Pro Lab 1.162 ver software. In gaze tracking analysis, fixation number, fixation time, saccades number, and the saccades amplitude were used. Fixation means that the gaze stops at one point and a saccade means movement of the pupil that occurs between fixation.

fNIRS Measures

In this study, the degree of activation was analyzed by measuring changes in blood flow in each channel after mapping subject's prefrontal lobe to 48ch according to the Brodmann region using NIRSIT equipment. This equipment uses near-infrared spectroscopy, and after irradiating the prefrontal lobe with near infrared rays of two wavelengths of 780 nm and 850 nm, the intensity of the returned light is measured with a sensor to check concentrations of oxidized hemoglobin and deoxidized hemoglobin according to the light absorption rate. Through this, activation of the prefrontal regions could be analyzed by checking changes in oxygen saturation in the blood of the prefrontal lobe region in a non-invasive manner.

Subjects sat in chairs and wore fNIRS equipment on the prefrontal lobe. The prefrontal lobe area was mapped to 48ch according to the Brodmann areas. Calibration was performed by removing noise caused by the scalp and noise caused by movement. Thereafter, a text reading task was performed and changes in the concentration of hemoglobin oxide (**HbO2**) in this process were measured. In addition, the baseline for activation of the prefrontal lobe, which was different for each individual, used measurement data on brain blood flow during stabilization before performing each subject's task. The prefrontal lobe area and the corresponding channel (48ch) classified according to the Brodmann areas, the measurement target of this study, are shown in Figure 1.

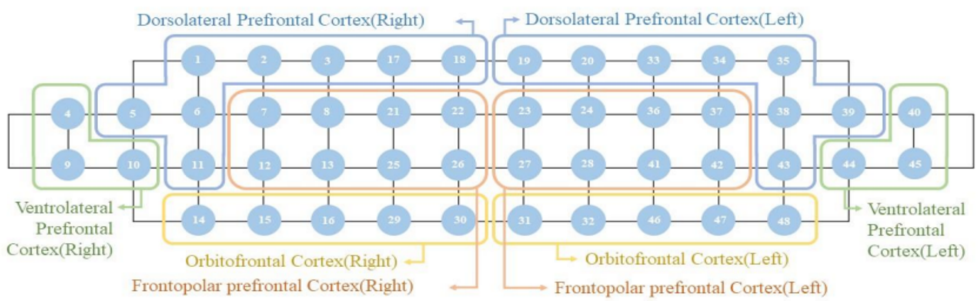

Figure 1: Prefrontal lobe regions and channels classified as Brodmann areas (OBELAB, 2022).

Reading Text and Task

In this study, subject was presented with a task of reading the text within 120 seconds and then summarizing contents of the text within 60 seconds. The reading task was performed twice (before and after exercise). The subject's reading task performance process was measured with a gaze tracking device and fNIRS. To prevent differences in reading depending on the type and length of text, this study presented all reading task text as an explanatory statement consisting of a total of four paragraphs and 750 to 800 characters (Korean). In addition, all texts were extracted from Korean language section fingerprints of the first year of high school for evaluating national academic achievement in Korea to prevent differences in reading according to the level of text content. The extraction and composition of the text were all made through five Korean language experts (3 PhDs in Korean language education and 2 on-site Korean language teachers in middle and high schools).

Experimental Procedure

Before commencing the experiment, this study received approval from the Research Ethics Review Board **(IRB)** of University D (IRB approval number: DUIRB-202109-23). The purpose, precautions, and procedures of the study were explained to all subjects, and their participation consent was obtained voluntarily. The height and weight of the subject who submitted the consent form were measured and the heart rate at rest was measured after taking a sufficient rest for five minutes. After completing the basic measurement, the fNIRS equipment was worn on the prefrontal lobe of the subject. The equipment was then calibrated when the subject was sitting in front of the monitor. After calibration of the fNIRS equipment was completed, calibration was performed for the gaze tracking equipment installed under the monitor.

After all calibration was completed, subjects closed their eyes and waited for five minutes. Each subject's brain blood flow at rest was measured for 30 seconds to determine the baseline for the degree of activation of the subject's prefrontal lobe during the waiting process. At the end of the wait, subjects performed a text read (**pre-read**) on the monitor for 120 seconds with the onset of the measurer. The measurer measured the subject's cerebral blood flow and gaze movement. After performing text reading, subjects summarized the text read for 60 seconds. After completing the reading task and measurement, subjects performed low or moderate intensity exercise for 20 minutes through a fixed indoor bicycle and rested for 5 minutes after the exercise. Subjects then sat back in front of the monitor and performed calibration and text reading (**post-reading**) and text summarization for the fNIRS equipment and gaze tracking devices in the same manner as before. To minimize interference between experiments, subjects took a sufficient rest for two weeks after the first measurement before participating in the second measurement.

Data Analysis

In this study, movement of the eyeball when reading text was measured using Tobii Pro Nano equipment. Measurement data were extracted using the Tobii Pro Lab analysis program. The text consisted of a total of four paragraphs. Area of Interest (**AOI**) was set according to the data extraction paragraph. Thereafter, data on fixation and saccades of the gaze of a set section was extracted.

Change in blood flow in the prefrontal lobe was measured using Obelab's NIRSIT equipment. For measured raw data, a low pass filter was applied as Discrete Cosine Transform **(DCT**) 0.1 and a high pass filter as DCT 0.005 to remove high frequency and low frequency noise. In addition, the Signal to Noise Ratio **(SNR)** of the baseline of the subject was calculated and channels with values less than 30 dB were excluded from the analysis. After calculating HbO2 through the Modified Beer-Lambert Law **(MBLL)** calculation process, raw material treated in this way was analyzed as 48 channels by averaging changes in the prefrontal lobe HbO2 during reading performance. Baseline for vestibular activation was utilized by averaging 30-second vestibular activation data values measured during stabilization. Changes in blood flow during 50 seconds after the start of reading were measured.

SPSS version 25.0 for windows was used for statistical treatment of eye movement and prefrontal lobe activation. All measurements are expressed as mean and Standard Deviation **(SD).** Two-way repeated measure ANOVA was conducted to analyze differences in dependent variables according to exercise intensity and time. In addition, a paired t-test was conducted to find out changes in dependent variable according to the period of exercise intensity. All statistical significance levels were set at $\alpha = 0.05$.

Results

Results of Eye Movement Tracking During Reading According to Exercise Intensity

Results of tracking the eye movement according to the intensity of exercise are shown in Table 2. As a result of the analysis, no statistically significant result was found for the saccades number or the saccade amplitude. On the other hand, at the fixation number ($p = 0.35$) and fixation time ($p = 0.44$) an interaction effect according to the intensity and timing of exercise was shown. In addition, the main effect according to the period was shown at the fixation number ($p = 0.29$). In other words, the fixation number and fixation time for the two groups varied according to the measurement period. They were increased in the low intensity group after exercise compared to those in the moderate intensity group.

Variable	Group	Pre	Post	Source	F	P
Saccades Number (times)	Low	223.55±62.79	260.27±71.19	Time	2.81	0.109
				Group	0.482	0.496
	Moderate	223.45±66.83	223.18±70.70	T×G	2.895	0.104
Saccades amplitude (degree)	Low	3.62±0.55	3.72±0.68	Time	0.221	0.644
				Group	0.001	0.981
	Moderate	3.76±0.50	3.58±0.53	T×G	2.4	0.137
Fixation number (times)	Low	255.55±66.16	326.64±99.66	Time	5.545	.029*
				Group	0.067	0.799
	Moderate	282.09±80.89	283.45±84.39	T×G	5.135	.035*
Fixation time(ms)	Low	55.47±18.22	67.54±20.53	Time	2.785	0.111
				Group	0.224	0.641
	Moderate	58.80±18.47	57.29±17.37	T×G	4.604	.044*
Data are presented as means ± SD. *p < .05, ** p < .01, *** p < .001						

Table 2: Results of eye movement tracking during reading.

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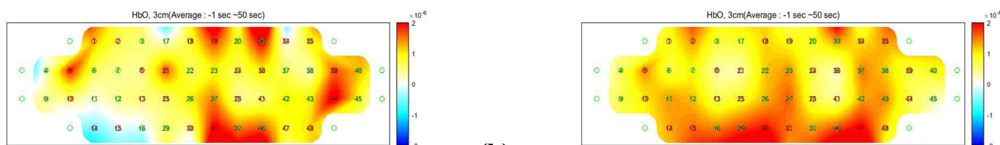
Results of Changes in Activity of the Prefrontal Lobe during Reading According to the Intensity of Exercise

Results of activation of the prefrontal lobe channel according to the intensity of exercise are shown in Table 3, Figure 2, and Figure 3. As a result of analyzing differences in 48 channels of fNIRS known to reflect activation of the prefrontal lobe, the interaction effect was statistically significant in channel 23 ($F = 4.911$, $p = 0.04$) and channel 30 ($F = 5.348$, $p = 0.033$). In addition, it was found that there was a statistically significant difference in the main effect between periods in channel 2($F = 8.381$, $p = 0.01$) and channel 15($F = 5.135$, $p = 0.036$). Analysis of differences according to timing by exercise intensity showed statistically significant differences in channel 2($t = -2.521$, $p = 0.033$), channel 15 ($t = -3.718$, $p = 0.005$), channel 30($t = -2.405$, $p = 0.04$) in low intensity exercise. And channel 47 ($t = -3.376$, $p = 0.008$) was showed statistically significant difference in moderate intensity exercise.

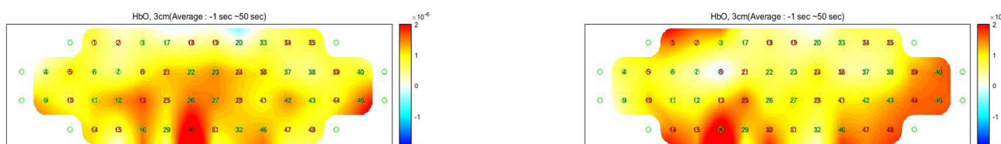
Group	Area	DPFC	FPC	OFC	VPFC
Low	Left	-	Ch23(+)	Ch47(+)	-
	Right	Ch2(+)	-	Ch12(+), Ch30(+)	-
Moderate	Left	-	Ch23(-)		-
	Right	Ch2(+)	-	Ch15(+), Ch30(-)	-

Table 3: Results of changes in the activity of prefrontal lobe during reading.



(a) **(b)**

Figure 2: Comparison of prefrontal activation results during reading: **(a)** before low intensity exercise; **(b)** after low intensity exercise. The left side of the figure is the right prefrontal lobe, and the right side is the left prefrontal lobe.



(a) **(b)**

Figure 3: Comparison of prefrontal activation results during reading: (a) before moderate intensity exercise; (b) after moderate intensity exercise. The left side of the figure is the right prefrontal lobe, and the right side is the left prefrontal lobe.

Discussion

Changes in Eye Tracking According to Exercise Intensity

Fixation time, number of fixation, saccade distance, and amplitude of saccade in eye tracking can provide quantitative and explicit information to infer a reader's cognitive process [22]. Among them, the fixation time and fixation number of times have meanings related to information processing of the reader. This is because during the gaze's stay, the reader enters and processes information from the text [23]. In general, the fixation time and the fixation number of times increase when the reader has difficulty processing information [24]. This is because as the fixation time and the fixation number of times increase, the amount of information to be processed in the text is large, or it is difficult to understand and predict the text [25]. Studies on gaze tracking of reading-disabled children and general children have also reported that the gaze fixation time of immature readers is long and gaze fixing occurs frequently [26].

On the other hand, the lower the reading proficiency or text difficulty, the lower the fixation time and fixation number of times [27-29]. One study of Korean text has found that more proficient readers have less fixation time and fixation number of times whereas more inexperienced readers have more fixation time and fixation number of times [21,30,31]. The acute exercise performed in this study is expected to activate cerebral and body control functions related to eye exercise or improve subjects' cognitive processing functions in relation to cognitive functions, making them read text like a more proficient reader.

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In this study, as a result of analyzing the eye movement during reading according to the intensity of exercise, there was a significant interaction between the number of fixation and the fixation time. In addition, there was a significant difference in the main effect of the number of fixation. Under the experimental conditions of this study, where text difficulty, subjects, and time limit were the same, results of gaze tracking of subjects showed that the fixation time and fixation number of times increased compared to pre-exercise reading after a low intensity exercise. In light of results of previous studies showing that the fixation time and number of fixation of skilled readers decreased, results of this study indicated that low intensity exercise could lead subjects to perform reading in a manner similar to inexperienced readers.

However, results of this study can be interpreted in other ways. Considering that the reading task of this study involved reading text several times within a time limit of 120 seconds rather than one reading of one text performed by the same subjects, the increase in fixation time and fixation number of times after low intensity exercise could be interpreted as an action result of a given time limit. If so, results of this study can be interpreted that fixation time and fixation number of times were significantly increased when subjects who processed text information more quickly focused on the text and repeatedly read it more frequently during a given time limit. In this regard, Kim [22] has also reported that fixation time and fixation number of times are increased for a skilled reader compared to those of an average reader because of repeated reading by a proficient reader who could quickly grasp the information of the text during the time limit. In addition, Holmqvist et al. [32] have reported that a long fixation time might be an active thinking process. Therefore, the selection of a valid interpretation among two different interpretabilities of gaze tracking results in this study is possible when gaze tracking results are understood in conjunction with changes in cerebral blood flow according to exercise intensity.

Changes in Activity of the Prefrontal Lobe According to Exercise Intensity

The frontal lobe of the cerebrum plays a role in controlling cognitive function. Cerebral prefrontal lobe is known to be activated when performing exercise or cognitive tasks [17]. Recently, various studies have been conducted to analyze effects of exercise on activation of the prefrontal lobe [33-36]. Results of this study (Figure 2 and Figure 3) showed overall activation patterns of the prefrontal lobe before and after exercise, confirming that aerobic exercise could affect activation of the prefrontal lobe during reading, especially in the lower part of the prefrontal lobe and after low intensity exercise.

In this study, it was found that channel 23 from the left Frontopolar Prefrontal Cortex (**FPC**) and channel 30 from the right Orbit of Frontal Cortex **(OFC)** had significant interaction effects. In both channels, the degree of activation increased after a low intensity exercise but decreased after a moderate intensity exercise. Channel 2 from the right Dorsolateral Prefrontal Cortex **(DPFC)** and channel 15 from the right OFC showed the statistically significant main effect on the time. In both channels, the degrees of activation increased after not only the low intensity, but also moderate intensity exercises. However, analysis of difference in activation of the prefrontal lobe before and after exercise in the exercise group showed significant activation in four channels: one right DPFC (channel 2), two right OFC (channels 15 and 30), and one left OFC (channel 47). After a moderate intensity exercise, a significant decrease in activation was confirmed in one channel (channel 23) of the left FPC. In the case of Ventrolateral Prefrontal Cortex **(VPFC),** it showed no statistically significant difference according to exercise intensity or timing.

Yanagisawa et al. [16] have reported that acute aerobic exercise can increase oxygenation of the cerebrum and activate the cortex of the left prefrontal lobe related to cognitive function performance. Meanwhile, Tsujii et al. [36] have reported that aerobic exercise in the elderly can activate the left prefrontal cortex. Moriya et al. [35] have reported that aerobic exercise in stroke patients can activate the right prefrontal cortex. In this study of healthy adult men and women found that low and moderate intensity aerobic exercises could activate both left and right prefrontal lobes at reading, particularly activating the right prefrontal cortex (low intensity: 3 channels; moderate intensity: 0 channels) rather than the left one (low intensity: 2 channels). In addition, it was confirmed that the activity of the prefrontal cortex could be reduced (low intensity: 0 channels, moderate intensity: 2 channels) when reading depending on the intensity of aerobic exercise.

When activation channels of the prefrontal lobe according to the intensity of exercise were compared and analyzed with positions of channels classified according to the Brodmann areas of Figure 1, a total of five channels were activated in low intensity exercise. Since these channels belonged to DPFC, FPC, and OFC excluding VPFC among prefrontal lobe regions, it was confirmed that the prefrontal region was entirely activated after low intensity exercise. Among them, a total of three channels (left: channel 47, right: channels 15 and 30) were activated, indicating that low intensity exercise could particularly activate the OFC located at the lower part of the prefrontal lobe. In moderate intensity exercise, a total of two channels were activated. It was found that these channels belonged to DPFC and OFC among prefrontal regions. On the other hand, in moderate intensity exercise, the activity was decreased in a total of two channels. These channels belonged to FPC and OFC among prefrontal regions.

Summarizing analysis results of this study, low and moderate intensity exercise activated left and right prefrontal lobes during reading, especially the right prefrontal lobe. In addition, five channels after low intensity exercise and two channels after moderate intensity exercise showed significant increases in activation, indicating that low intensity exercise could activate the prefrontal lobe more than moderate intensity exercise. Looking at the activation area of the prefrontal lobe, areas commonly activated after low and moderate intensity exercises were DPFC and OFC. Low intensity exercise mainly activated the OFC region (a total of three channels) and activated channels belonging to the left FPC. In addition, there was no significant decrease in the activation of the prefrontal lobe after low intensity exercise. However, two channels (channels belonging to FPC, OFC) showed significant decreases in activation after moderate intensity exercise. Moderate intensity exercise might reduce the degree of activation of the prefrontal lobe, unlike low intensity exercise.

The left and right OFCs are interconnected with other areas of the brain related to emotions, such as the hypothalamus, amygdala, brain island, and target cortex. Therefore, they are areas most deeply involved in the integration of emotions and decision-making. It has also been reported that predicting outcomes and making appropriate choices in integration with emotions in decision-making are related to activation of this area [37,38]. DPFC and FPC are known to play an important role in performing attentional concentration and central execution during cognitive activities [39]. Left and right DPFCs are areas reported as centers of cognitive execution that can perform central decision-making functions mainly related to working memory.

It has been reported that FPC performs functions related to attention focus, control, goal setting, and so on. It also has functions related to goal consciousness and meta-cognitive functions on the right and motivation or reward expectations on the left [37,40]. Putting these contents together and interpreting results of this study, low and moderate intensity exercise could activate DPFC, which the backbone of cognitive execution related to working memory and intention execution during reading and OFC, which integrates emotions and decision making and selects and predicts appropriate cognitive processes. Low intensity exercise mainly activates the OFC and activates the FPC, especially the left FPC, which performs functions related to attention and control, goal setting, etc. Thus, low intensity exercise is expected to activate cognitive functions such as intention execution, attention, prediction, and selection during reading.

Moderate intensity exercise can also activate functions such as cognitive execution and outcome prediction and selection by activating DPFC and OFC when reading, however the degree of activation of channels belonging to OFC and FPC is decreased. Thus, the effect of activating the reading function is expected to be insignificant compared to low intensity exercise. As reported in previous studies by Subudhi et al. [18] and Rooks et al. [17], exercise fatigue caused by moderate intensity exercise decreases the oxygenated hemoglobin and blood flow of the prefrontal lobe can negatively affect the activation of some prefrontal lobe functions.

Overall

In this study, effects of acute low and moderate intensity exercise using exercise bike on changes in eye movement and prefrontal lobe blood flow in adults reading were measured through eye tracking and fNIRS to find out the maximum exercise effect on cognitive and reading function. As a result of the analysis, it was confirmed that low intensity exercise rather than moderate intensity exercise using exercise bike could improve reading and cognitive functions of subjects [41]. After low intensity exercise, the fixation time and number of fixation for a subject's text increased during reading. It was possible to interpret that subjects had difficulty reading and understanding the text or that subjects repeatedly read the text for a limited time due to faster reading and understanding of the text. In addition, low intensity exercise activated the prefrontal lobe of subjects such as DPFC, OFC, and FPC on reading (a total of five channels).

In particular, OFC, which integrates subjects' emotions and decision making of subjects to select and predict appropriate cognitive processes, was mainly activated. If results of this prefrontal lobe activation analysis are combined with eye tracking results, it could be interpreted that the increase in fixation time and number of fixation after low intensity exercise is the result of faster text information processing by subjects and repeatedly reading text over a given time. On the other hand, no significant eye tracking results were found after acute moderate intensity exercise. In addition, the moderate intensity exercise activated two channels belonging to DPFC and OFC of the prefrontal lobe upon reading. However, the degree of activation of two channels belonging to FPC and OFC decreased. As a result, it is considered that low intensity exercise is more effective in improving reading and cognitive abilities of subjects than moderate intensity exercise.

Conclusions

Conclusions drawn through results of this study are as follows. First, acute aerobic exercise through exercise bike can partially improve cognitive and reading functions by activating eye movement and prefrontal lobe during reading. Second, among acute low and moderate intensity exercises through exercise bike, the intensity of exercise that is more efficient in improving cognitive and reading functions is a low intensity exercise with a target heart rate of 40% than a moderate intensity exercise with a target heart rate of 60% based on 20 minutes.

Limitations of this study and suggestions for subsequent studies are as follows. First, in this study, subjects were divided into a low intensity exercise execution group with a target heart rate of 40% and a moderate intensity exercise execution group with a target heart rate of 60%, and results were derived through differences in eye movement and prefrontal lobe activation. In subsequent studies, it is necessary to compare various intensities and exercise time groups to detail the aerobic exercise time and level, which are efficient in activating cognitive function. Second, in this study, exercise and measurement were performed for adults aged 23.75 ± 3.60 years. Since there are differences in body control ability, brain plasticity, and reading ability depending on the age of the subject, follow-up studies need to examine the intensity of exercise and perform measurement according to age group to improve cognitive and reading skills.

Acknowledgments

Not applicable.

Authors' Contributions

EHK-designed the study and the methodology. TJK and WYL-provided the software, contributed to the resource and data curation, supervised the study. WYL and TJK-contributed to the formal analysis, revised the manuscript. TJK-contributed to data curation. EHK-drafted the manuscript. WYL-contributed to data visualization. EHK-were responsible for project administration. All authors contributed to the editorial changes in the manuscript. All authors have read and approved the final manuscript.

Competing Interests

The authors declare no conflict of interest.

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