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Effects of High Oxygen Concentration on Driving Performance and Cerebral Hemodynamic Response

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Abstract: The positive effect of a high oxygen concentration on human cognitive ability for single tasks has been proven in various ways; however, few studies have investigated its effect on complex cognitive tasks. The aim of this study was to investigate the effect of a high oxygen concentration in driving situations that require complex cognitive abilities. The experiment was conducted in a laboratory equipped with a car simulator with 10 volunteer subjects. Driving was performed under normal and high-oxygen-concentration conditions. Various driving parameters and oxyhaemoglobin (HbO) levels in certain brain areas were measured during the experiments. The results show that vehicle velocity was maintained more consistently in the high-oxygen-concentration condition, and the HbO concentration increased (indicating greater activation) in the prefrontal and parietal cortices.

Keywords: cerebral hemodynamic response; driving performance; fNIRS; high oxygen concentration; oxyhaemoglobin

1 INTRODUCTION

Oxygen is present in the atmosphere at a concentration of approximately 21 %, and it is consumed in various biological processes essential to the survival of plants and animals. The oxygen concentration in human blood is maintained above 95 %, enabling energy production within cells and enabling organs and tissues to perform their functions [1]. In particular, the brain consumes a large amount of oxygen (approximately 20 % of the human body's oxygen consumption) because of the dense concentration of nerve cells [2, 3]. It is also the most sensitive organ to oxygen deficiency [4]. Irreversible brain damage occurs when the brain does not receive sufficient oxygen, leading to a decline in high-level cognitive functions, including degradation of processing speed, memory, and executive function [5].

Because of the essential role of oxygen in the brain, research is being conducted on improving cognitive processing ability by artificially oversupplying oxygen. Some studies show that high oxygen concentration has a positive effect on cognitive processing ability [6-9]. Chung et al. [7] reported that visuospatial performance improved and blood oxygen saturation increased when 30 % oxygen was supplied compared to when 21 % oxygen was supplied. In addition, an increase in brain activity has been reported under 30 % oxygen concentration conditions using functional magnetic resonance imaging (fMRI). In addition, 30 % oxygen supply improves memory, verbal cognition, and working memory performance. However, these studies have been conducted only on a single task in a static environment. Therefore, the effects of high oxygen concentration on the performance of complex cognitive processing tasks must be verified.

Driving requires high levels of information processing because various factors, such as interactions with in-vehicle devices and changes in driving conditions (such as nearby vehicles, infrastructure, and weather) must be considered [10-13]. Driving requires high performance on complex cognitive processes, such as attention, visuospatial perception ability, memory, and problem-solving ability [14, 15].

Whereas previous studies have shown that high oxygen concentration affects cognitive processing for a single task, the aim of this study was to observe the effect of high concentrations of oxygen in a driving environment and verify the hypothesis that high oxygen concentration can activate the brain and improve performance on tasks requiring a high level of cognitive processing. For objective verification, brain activation via functional near-infrared spectroscopy (fNIRS) and driving performance were observed using driving performance data.

2 METHODS
2.1 Participants

Through a subject recruitment announcement, ten men, all licensed drivers in their 20s, voluntarily participated in the experiment (Tab. 1). Their average driving experience was 2.2 years. They had no history of brain disease or related surgery, and they were recommended to get more than 7 h of sleep the night before the experiment. On the day of the experiment, activities such as caffeine and drug consumption, smoking, and drinking that could affect fNIRS measurements were prohibited. Before starting the experiment, were explained to all participants, and written consent to participate was obtained.

Table 1 Experimental subject data

Gender	Number of subjects	Mean of age (SD)	Driving experience
Male	10	24.78 (±1.63)	2.20 (±1.23)

2.2 Oxygen Condition

Oxygen was supplied by connecting an oxygen respirator to an oxygen cylinder composed of oxygen and nitrogen. Cylinder 1 supplied 21 % oxygen and 79 % nitrogen, and Cylinder 2 supplied 30 % oxygen and 70 % nitrogen. The oxygen pressure was set at 68.95 kPa.

2.3 Driving Condition

The driving simulator used in the experiment was a GDS-3000s (Gridspace, South Korea) model, and the driving devices (accelerator, foot brake, and steering wheel) and display devices (speedometer, RPM meter, and trafficator) were implemented in the same manner as in an actual vehicle. A driving simulation environment was presented using three 32-in LCD monitors. The driving environment was a round trip on a six-lane highway; as shown in Fig. 1, a course of 3.4 km wide and 2.4 km long was driven in two lanes at a speed of 100 km/h.

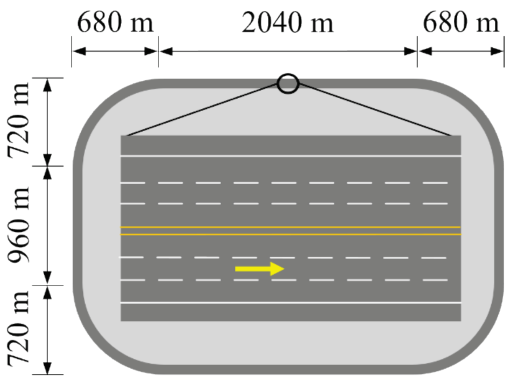

Figure 1 Driving environment

2.4 Experimental Process

The experimental process is shown in Fig. 2. The participants were asked to rest (Rest phase) for 20 min with their eyes closed. Then, oxygen was supplied for 20 min during the driving exercise (Driving phase). Subsequently, the same experiment was repeated for each subject with only a change in the oxygen concentration. At this time, the order of oxygen concentration was counterbalanced. In addition, the subjects were unaware of the oxygen concentration presented.

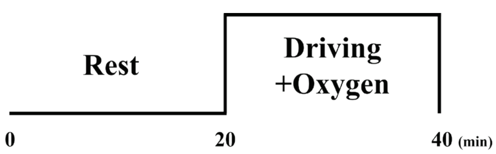

Figure 2 Experimental process

2.5 Measuring and Analysing Driving Performance Data

The parameters of the driving data were vehicle position, velocity, engine speed (RPM), percentage of the accelerator pedal manipulated (e.g., 100 %, the accelerator pedal fully depressed), and percentage of the steering wheel manipulated (100 %, the steering wheel fully rotated), and were measured at a sampling rate of 1 Hz. The last 5 min (15-20 min) of data in the driving phase were used for the analysis, and the parameters (Velocity, RPM, ACC, Steering) corresponding to the cornering section were extracted from the vehicle's location data (Tab. 2). The coefficient of variation was used as an indicator of driving performance. Therefore, the coefficients of variation for the velocity (CV_Velocity), RPM (CV_RPM), accelerator manipulation (CV_ACC), and steering wheel manipulation (CV_Steering) were calculated. Subsequently, a paired t-test was performed to compare the oxygen conditions (21 % and 30 %) using SPSS version 25 (IBM, USA).

Table 2 Driving performance data parameters

Parameter	Position		Velocity	RPM	ACC	Steering
	X	*Z*				
Unit	m	m	km/h	-	%	%

2.6 Cerebral Blood Flow Response Measurement and Analysis Method

Cerebral blood flow was measured using a NIRSport2 device (NIRx, Germany). This device consists of a source that emits near-infrared rays of two wavelengths (760 and 850 nm) and a light detector. Optical data (the amount of light detected) were measured at a sampling rate of 5.08 Hz. Thirty-two optodes (source: 16, detector: 16) were attached to the prefrontal, frontal, and parietal areas using the 10-20 system, and optical data from 49 channels were acquired (Fig. 3).

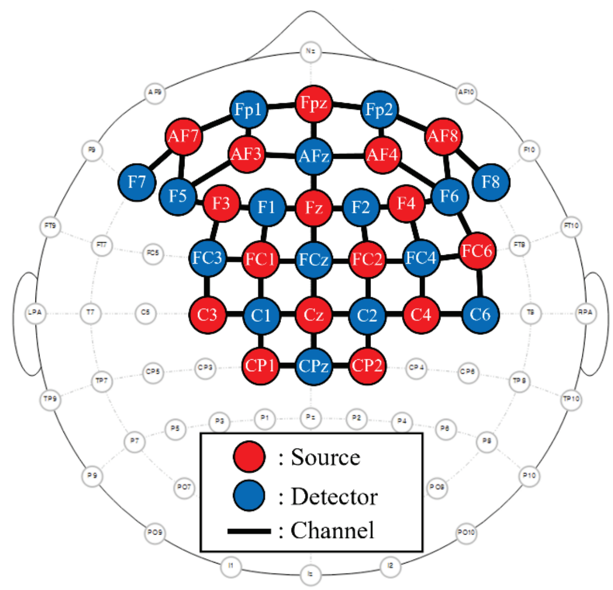

Figure 3 Optode attachment locations

The optical data obtained through fNIRS were converted to hemodynamic data using nirsLAB software (NIRx Medical Technologies, USA). First, bandpass filtering (0.01-0.2 Hz) was performed to remove physiological noises such as heartbeat and respiration. Subsequently, after adjusting the baseline of the entire dataset using data from the rest of the section, the oxyhaemoglobin (HbO) concentration was extracted using the modified Beer-Lambert law. The differential path length factor (DPF) was set to 7.25 (W1) and 6.38 (W2) [16-18].

The HbO concentration data extracted in the form of a time series were analysed using MATLAB version R2021b (MathWorks, USA). First, the average HbO concentration value in the last 5 min (15-20 min) of the driving phase was calculated for each channel. Subsequently, the brain was divided into six areas (left prefrontal, right prefrontal, left frontal, right frontal, left parietal, and right parietal) and the HbO concentration of the channels corresponding to each area was averaged (Tab. 3). For the comparison of oxygen concentrations, a paired t-test was performed for the two conditions (21 % and 30 %) using SPSS.

Table 3 Channels corresponding to each brain area

Brain area	Channel (Source-Detector)
Left prefrontal	Fpz-Fp1, AF3-AFz, AF3-Fp1, AF3-F5, AF7-Fp1, AF7-F5, AF7-F7
Right prefrontal	Fpz-Fp2, AF4-AFz, AF4-Fp2, AF4-F6, AF8-Fp2, AF8-F6, AF8-F8
Left frontal	Fz-F1, F3-F1, F3-F5, F3-FC3, FC1-FCz, FC1-F1, FC1-FC3, FC1-C1, C3-FC3
Right frontal	Fz-F2, F4-F2, F4-F6, F4-FC4, FC2-FCz, FC2-F2, FC2-FC4, FC2-C2, C4-FC4
Left parietal	Cz-C1, C3-C1, CP1-C1, Cp1-Cpz
Right parietal	Cz-C2, C4-C2, CP2-C2, CP2-CPz

3 RESULTS

3.1 Driving Performance

A comparison of the driving data for the two oxygen conditions is shown in Fig. 4. CV_Velocity was 0.04 ± 0.02 under 21 % oxygen and 0.02 ± 0.01 under 30 % oxygen, which means that the variation under high oxygen concentration was significantly small ($p < 0.05$). CV_RPM and CV_ACC also significantly decreased under 30 % oxygen compared to those under 21 % oxygen ($p < 0.05$). In contrast, CV_Steering showed no significant difference between the two oxygen conditions (Tab. 4).

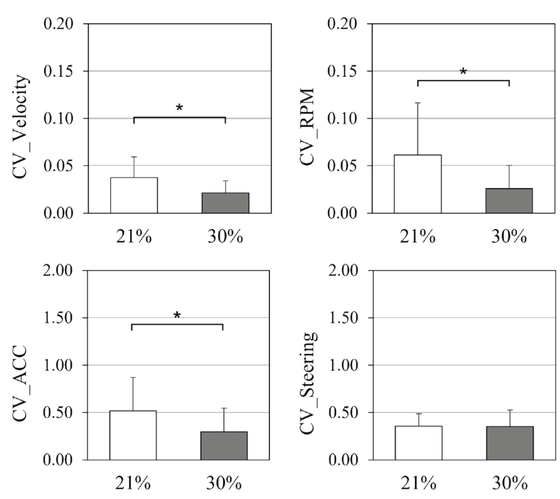

Figure 4 Results of driving performance data analysis

Table 4 Paired t-test results for oxygen conditions on driving performance

Parameter	Condition, %	Mean (*SD*)	*t*	*p*	*Cohen's d*
CV_Velocity	21	0.04 (± 0.02)	2.63	0.028	0.87
	30	0.02 (± 0.01)			
CV_RPM	21	0.06 (± 0.06)	2.66	0.026	0.69
	30	0.03 (± 0.02)			
CV_ACC	21	0.52 (± 0.35)	2.39	0.041	0.78
	30	0.30 (± 0.25)			
CV_Steering	21	0.36 (± 0.13)	0.03	0.980	0.01
	30	0.35 (± 0.17)			
Cohen's d = Mean difference / SD_{pooled}					

3.2 Cerebral Hemodynamic Response

A comparison of the HbO concentration by oxygen condition, as shown in Fig. 5, indicated that the HbO concentration increased under 30 % oxygen compared to 21 % oxygen. As shown in Tab. 5, statistically significant changes were observed in three of the six brain regions (left prefrontal, right prefrontal, and right parietal; $p < 0.05$). The HbO concentration in the left prefrontal increased by 1.90×10^{-5} mM, from 0.19×10^{-5} mM under 21% oxygen to 2.09×10^{-5} mM under 30 % oxygen ($t = 3.089$, $p = 0.013$). In the case of the right prefrontal region, it increased by 1.95×10^{-5} mM, from 0.21×10^{-5} mM under 21 % oxygen to 2.16×10^{-5} mM under 30 % oxygen ($t = 3.021$, $p = 0.014$). In the case of the right parietal region, it increased by 0.79×10^{-5} mM, from 0.50×10^{-5} mM under 21 % oxygen to 1.29×10^{-5} mM under 30 % oxygen ($t = 2.463$, $p = 0.036$).

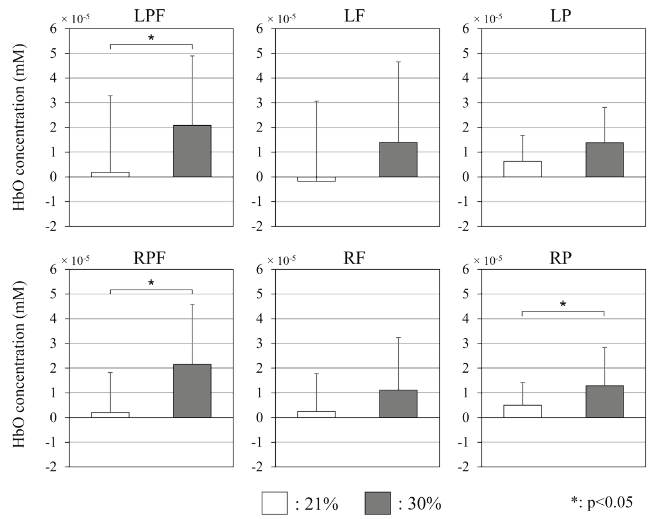

Figure 5 Hemodynamic response

Table 5 Hemodynamic response paired t-test results based on oxygen

Brain area	Condition, %	Mean (*SD*)	*t*	*p*	*Cohen's d*
Left prefrontal	21	0.19 (± 3.10)	−3.09	0.013	−0.61
	30	2.09 (± 2.80)			
Right prefrontal	21	0.21 (± 1.61)	−3.02	0.014	−0.89
	30	2.16 (± 2.43)			
Left frontal	21	−0.18(± 3.24)	−1.45	0.182	−0.46
	30	1.40 (± 3.25)			
Right frontal	21	0.25 (± 1.11)	−2.00	0.077	−0.44
	30	1.11 (± 2.12)			
Left parietal	21	0.63 (± 1.05)	−2.05	0.070	−0.57
	30	1.39 (± 1.43)			
Right parietal	21	0.50 (± 0.92)	−2.46	0.036	−0.58
	30	1.29 (± 1.55)			
Cohen's d = Mean difference / SD_{pooled}					

4 DISCUSSION

This study was conducted to investigate the effect of 30 % oxygen concentration on driving performance. HbO concentration was measured using the cerebral hemodynamic response as a physiological indicator, and fluctuations in velocity, RPM, ACC, and steering wheel were observed to assess driving performance.

The cerebral hemodynamic response analysis showed that the HbO concentration increased in the high oxygen concentration condition compared to that in the normal oxygen concentration condition. Clear differences were observed in the left prefrontal, right prefrontal, and right parietal regions. Driving performance analysis showed that the coefficients of variation of velocity, RPM, and ACC were smaller under high oxygen concentration conditions than under normal oxygen concentration conditions. In other words, the velocity was maintained at a constant value without unnecessary manipulation under high oxygen concentration conditions.

These results show that the effect of a high oxygen concentration is significant, even in complex driving situations that simultaneously require various cognitive resources, and the results suggest that improvement in a single cognitive ability by high-concentration oxygen also affects complex cognitive abilities.

In particular, the prefrontal cortex is associated with various factors, including memory and decision-making, and it is thought that high oxygen concentration activates the corresponding area, thereby increasing driving performance. Chung et al. observed that the prefrontal lobe was activated when 30 % oxygen concentration was present, and task performance also improved [8, 19]. In addition, Hannah reported that drivers with longer driving experience exhibited a higher prefrontal cortical activation than did novice drivers [20].

Among the cognitive abilities required for driving, the parietal cortex is related to visuospatial perception. Chung et al. observed that the parietal cortex was activated through the supply of high-concentration oxygen (30 %) when performing a visuospatial task. In addition, activation of the corresponding areas leads to improvements in visuospatial cognitive performance [8]. As an interpretation of this, it is judged that high concentration oxygen provides sufficient oxygen to the brain and activates the neural network, thereby improving cognitive ability.

In addition, Just et al. compared brain activation and driving performance in conditions where only driving was performed and where driving and additional work were performed simultaneously [21]. They found that the parietal area was more activated when only driving was performed compared to the dual-task condition, and driving performance improved.

Another interpretation of the effect of high oxygen concentration while driving is the reduction of driving fatigue. Sung et al. observed changes in driving performance under low, normal, and high oxygen concentration conditions [22]. They found that the reaction time for operating the brake pedal decreased under high-concentration oxygen conditions compared to low-concentration oxygen conditions. These results indicate that the supply of high-concentration oxygen reduced driving-induced mental fatigue, thereby improving driving ability. Their work differs from the present study in that driving ability was improved over a long period of time (120 min after starting driving); however, the improvement in driving ability was attributed to a reduction in fatigue 30 min after the start of driving. High oxygen concentration therefore reduces driving fatigue in a relatively short period of time, which improves driving performance.

Taken together, it is clear that high oxygen concentration causes activation by supplying sufficient oxygen to brain regions related to driving (prefrontal and parietal), thereby improving cognitive processing ability and thus driving performance. Additionally, the supply of high-concentration oxygen reduces driving fatigue, which also improves driving performance. In other words, high oxygen concentrations are believed to have a positive effect even in driving situations requiring complex cognitive abilities.

5 CONCLUSION

In conclusion, the findings of this study suggest a significant positive impact of high oxygen concentration (30 %) on driving performance, as evidenced by changes in cerebral hemodynamic response and driving-related parameters. The increased HbO concentration in key brain regions, such as the left prefrontal, right prefrontal, and right parietal areas, indicates enhanced cognitive processing abilities during driving tasks.

The study observed reduced variability in velocity, RPM, and ACC under high oxygen concentration conditions, highlighting a more stable and controlled driving performance. Notably, the prefrontal cortex, associated with memory and decision-making, and the parietal cortex, linked to visuospatial perception, were activated, contributing to improved driving abilities.

Furthermore, the study suggests that high oxygen concentration may play a role in mitigating driving fatigue, as reflected in decreased reaction times for brake pedal operation. This reduction in mental fatigue within a relatively short period could contribute to sustained improvements in driving performance.

This study has a limitation in that the demographic characteristics of the study participants were limited. According to previous studies, high oxygen concentrations differ in the amount of oxygen contained in the blood (blood oxygen saturation) depending on age. Driving performance also varies depending on age and sex; therefore, further research that considers these factors could lead to a more in-depth understanding of the effects of high-concentration oxygen. In addition, it is necessary to observe whether the effect of high concentration oxygen appears in actual driving situations rather than long-term driving situations or simulation situations. In summary, the positive effects of high oxygen concentration on driving performance, cognitive processing, and fatigue reduction indicate its potential as a promising intervention in enhancing safety and efficiency, even in complex driving scenarios requiring various cognitive resources.

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