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Author(s)	Yoshida, Kazuki; Sawamura, Daisuke; Inagaki, Yuji; Ogawa, Keita; Ikoma, Katsunori; Sakai, Shinya
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Title

Brain activity during the flow experience: a functional near-infrared spectroscopy study

Kazuki Yoshida[1,2], Daisuke Sawamura[1,3], Yuji Inagaki[4], Keita Ogawa[3], Katsunori Ikoma[5], Shinya Sakai[6]

[1]Division of Health Sciences, Graduate School of Health Sciences, Hokkaido University

[2]Department of Occupational Therapy, Faculty of Human Science, Hokkaido Bunkyo University

[3]Department of Rehabilitation, Hokkaido University Hospital

[4]Department of Rehabilitation and Physical Medicine, Graduate School of Medicine, Hokkaido University

[5]Department of Rehabilitation Medicine, Hokkaido University

[6]Department of Functioning and Disability, Faculty of Health Sciences, Hokkaido University

Corresponding author: Shinya Sakai, PhD.

Department of Functioning and Disability, Faculty of Health Sciences, Hokkaido University, Sapporo, Japan.

N-12 W-5 Kita-ku, Sapporo 060-0812, Japan

Tel/Fax: +81 11 706 3388

E-mail: sakai@hs.hokudai.ac.jp

Abstract

Flow is the holistic experience felt when an individual acts with total involvement. Although flow is likely associated with many functions of the prefrontal cortex (PFC), such as attention, emotion, and reward processing, no study has directly investigated the activity of the PFC during flow. The objective of this study was to examine activity in the PFC during the flow state using functional near-infrared spectroscopy (fNIRS). Twenty right-handed university students performed a video game task under conditions designed to induce psychological states of flow and boredom. During each task and when completing the flow state scale for occupational tasks, change in oxygenated hemoglobin (oxy-Hb) concentration in frontal brain regions was measured using fNIRS. During the flow condition, oxy-Hb concentration was significantly increased in the right and left ventrolateral prefrontal cortex. Oxy-Hb concentration tended to decrease in the boredom condition. There was a significant increase in oxy-Hb concentration in the right and left dorsolateral prefrontal cortex, right and left frontal pole areas, and left ventrolateral PFC when participants were completing the flow state scale after performing the task in the flow condition. In conclusion, flow is associated with activity of the PFC, and may therefore be associated with functions such as cognition, emotion, maintenance of internal goals, and reward processing.

Keywords

flow experience; fNIRS; brain activity; prefrontal cortex; video game task

Introduction

Flow is the holistic experience that occurs when an individual acts with total involvement [1]. Flow is a psychological state that is characterized by a high level of attention with a low sense of effort, low self-awareness, and a sense of control and enjoyment, and occurs during the performance of tasks that are challenging but matched in difficulty to the skill level of the individual [2,3]. The state of flow has been studied in a wide range of tasks, from chess playing to rock climbing, and is described in remarkably similar terms across activities.

Understanding the brain activity that occurs during a state of flow is critical to understanding the state of absorption and optimal performance, yet the brain activity that occurs during a state of flow has not been investigated in detail. A positron emission tomography (PET) study revealed a positive correlation between flow proneness in daily life and dopamine D2 receptor availability in the dorsal striatum [4]. This study suggested that flow proneness is associated with dopaminergic transmission in the dorsal striatum, which is associated with reward processing, impulse control, and positive affect [5,6]. Klasen et al. [7] used functional magnetic resonance imaging (fMRI) to evaluate brain activity during flow and demonstrated increased activity in midbrain reward structures as well as a complex network of sensorimotor, cognitive and emotional brain circuits during a state of flow. However, the level of flow was not assessed, and it is not clear whether participants were able to enter a full state of flow when their heads were fixed in the magnetic resonance scanner. In addition, the brain areas that were activated included a large motor network (including the cerebellum and motor and premotor areas) and may have been confounded by the motor requirements of the experimental task.

Anatomically, the prefrontal cortex (PFC) has connections with the anterior cingulate cortex and limbic regions, such as the amygdale, that process emotion [8]. Functionally, the dorsolateral PFC (DLPFC) is involved in attention and concentration [9,10], the frontal pole area (FPA) is involved in the simultaneous performance of multiple tasks, particularly the maintenance of high-order internal goals during the performance of other sub goals [11,12], and the orbitofrontal cortex is involved in the processing of emotion, reward, and subjective pleasantness and unpleasantness [13]. It is assumed that flow is closely related to attention, emotion, and reward [2,3]; functions that are processed by the prefrontal lobe. However, the association between flow and activity in the prefrontal lobe has not directly been investigated.

Functional near-infrared spectroscopy (fNIRS) can be used to noninvasively monitor cerebral hemodynamics. fNIRS is less vulnerable to head and body motion artifact than fMRI, has greater temporal resolution, and can be performed while subjects perform tasks in a natural and comfortable environment. fNIRS is therefore an ideal method by which to evaluate brain activity during the flow experience. The aim of this study was to describe the activity of the PFC during flow and to examine the role of prefrontal areas in the flow experience.

Methods

Participants

Twenty right-handed healthy university students (10 females) participated in this study (age range, 21–25 years; mean ± standard deviation age, 22.3 ± 1.2 years, mean duration of education, 15.3 ± 1.2 years). No participants had any neurological or psychiatric history, or any medical history affecting their cognitive function. The Ethics Committee of the Faculty of Health Sciences at Hokkaido University approved the study protocol (approval number 12-91) and all participants provided written informed consent.

Experimental task

The Tetris® computer game was used as the experimental task. In this game, blocks of seven different shapes fell at a constant speed in a random order. Participants were required to manipulate the position of these blocks using keys on a computer keyboard. The playing field was 14 cells wide by 24 cells high, and each game ended when the blocks were stacked to the top of playing field.

The task was performed under two different conditions designed to induce psychological states of boredom and flow. In the boredom condition the level of skill required to complete the game was much lower than that of any healthy young person. The blocks descended at a rate of one cell every 1200 ms. In the flow condition the level of skill required to complete the game was matched to the skill level of the participant. The blocks initially descended at a rate of one cell every 800 ms, and this decreased by 33 ms every 20 s. Participants were also given the option of accelerating the falling speed of the blocks by pressing the down arrow key. Participants received an explanation of the game and practiced the game under the flow condition for 2 min before beginning the experiment.

Evaluation of flow state

The flow state scale for occupational tasks was used to evaluate flow state. The scale has 14 items, each rated on a seven-point Likert scale, and measures comparative change in flow state with good reliability and validity [14].

Experimental procedure

The experiment was conducted in a block design in which the experimental task was performed four times: Twice under the boredom condition and twice under the flow condition. The order of the conditions was counterbalanced as follows: flow-boredom-flow-boredom or boredom-flow-boredom-flow. Each block lasted 6 min and consisted of four parts: (1) Participants read the flow state scale for 30 s and responded "undecided" to each item, (2) Participants performed the experimental task for 4 min, (3) Participants completed the flow state scale in 1 min, and (4) Participants rested while looking at a monitor for 30 s. The total imaging time was 24 min.

fNIRS

fNIRS was performed using the multichannel fNIRS optical topography system (LABNIRS, Shimadzu Corporation, Kyoto, Japan) with three wavelengths of near-infrared light (780, 805, and 830 nm). Samples were recorded every 57 ms. fNIRS probes were arranged in a 5 × 7 matrix of 17 illuminating probes and 18 detecting probes arranged alternately with an inter-probe distance of 3 cm, resulting in 58 channels. The probes were positioned over the PFC. Probe 8 (between channels 3 and 4) was placed over Fpz, and the midline of the matrix (channels 10, 23, 36, and 49) overlapped the medial line (Fig. 1). fNIRS optode positions and several scalp landmarks (Cz, Nz, and right and left pre-auricular points) were digitized using a three-dimensional magnetic space digitizer (FASTRAK; Polhemus, Colchester, VT, USA). Probabilistic registration [15] was used to register fNIRS data to Montreal Neurological Institute standard brain space through the international 10-20 system. The optical fNIRS data were analyzed according to the modified Beer-Lambert-Law [16] to quantify changes in oxygenated hemoglobin (oxy-Hb), deoxygenated hemoglobin, and total hemoglobin concentration [17]. All analyses were performed on the change in oxy-Hb concentration.

Statistical analysis

fNIRS data were analyzed using the NIRS-SPM toolbox [18] to identify general regions of activation. Two comparisons were made: (1) the 20 s prior to the start of the experimental task vs. the 30 s after the end of the experimental task, i.e., when participants were completing the flow state scale before and after performing the task, and (2) the first 30 s of task performance vs. the last 30 s of task performance. Activated channels were grouped into six regions of interest (ROIs) using LABNIRS, as described by Yanagisawa et al. [19]. Briefly, the estimated anatomical location of each channel was determined according to the LBPA40 multichannel atlas [20] and three or four neighboring channels were combined to form each ROI. The ROIs were the left DLPFC (L-DLPFC), left ventrolateral PFC (L-VLPFC), left FPA (L-FPA), right DLPFC (R-DLPFC), right ventrolateral PFC (R-VLPFC), and right FPA (R-FPA) (Fig. 1). This procedure is valid because optical properties of neighboring channels are similar [21].

Brain activity was evaluated in two situations (during performance of the experimental task and during completion of the flow state scale) and under two conditions (flow and boredom). The final portion of the experimental task is likely to represent a deeper flow or boredom state than the initial portion, and the effect of task difficulty for analysis has to be minimized as much as possible. Therefore, the average oxy-Hb concentration was calculated for the duration of the 4-min experimental task (0–240 s) and for the final 30-s of the experimental task (210–240 s), and the change in oxy-Hb concentration during each period was calculated by subtracting baseline oxy-Hb concentration, measured in the 5 s before task onset, from these values. The average oxy-Hb concentration was also calculated for the final 20 s of the pre-experimental task flow state scale and the first 30 s of the post-experimental task flow state scale, and the change in oxy-Hb concentration during each period was calculated by subtracting baseline oxy-Hb concentration, measured in the first 5 s of the flow state scale periods, from these values. The changes in oxy-Hb concentrations were compared between the two periods in each situation (i.e., 0–240 s vs. 210–240 s for activity during performance of the experimental task, and pre- and post-experimental task for activity during completion of the flow state scale) in each condition (flow and boredom) using paired *t*-tests. The flow state scale score was compared across flow and boredom conditions using a paired *t* test. Values of $p < 0.05$ were considered to indicate statistical significance.

Results

Data from five participants were excluded from the analysis due to technical problems (a shift in probe position or incorporation of noise, $n = 2$ participants) or the absence of a flow state in the flow condition (a lower flow state scale score in the flow condition than in the boredom condition, $n = 3$ participants). Results are presented for the remaining 15 participants (age range, 21–24 years; mean ± standard deviation age, 22.0 ± 1.03 years; nine females). The flow state scale score was higher in the flow condition (mean ± SD score, 71.3 ± 9.1) than in the boredom condition (mean ± SD score, 41.3 ± 6.3, $t = 9.78$, $df = 14$, $p < 0.05$).

The NIRS-SPM analysis identified significant activation around the FPA, VLPFC, and DLPFC but no significant activation around motor areas including the premotor area and supplementary motor area. The activated channels were grouped into six ROIs using LABNIRS.

The change in oxy-Hb concentration in the R-VLPFC ($t(14) = -3.22$, $p < 0.01$) and L-VLPFC ($t(14) = -2.58$, $p < 0.05$) was greater during the final 30 s of the experimental task (210–240 s) than throughout the entire experimental task (0–240 s) in the flow condition (Fig. 2A) but not during the boredom condition (Fig. 2C). The change in oxy-Hb concentration in the R-DLPFC ($t(14) = 2.691$, $p < 0.05$), R-FPA ($t(14) = 3.245$, $p < 0.01$), L-VLPFC ($t(14) = 2.256$, $p < 0.05$), L-DLPFC ($t(14) = 2.463$, $p < 0.05$), and L-FPA ($t(14) = 2.496$, $p < 0.05$) was greater during completion of the flow state scale after the experimental task than during completion of the flow state scale before the experimental task in the flow condition (Fig. 2B). The change in oxy-Hb signal in the R-VLPFC ($t(14) = 2.941$, $p < 0.05$) and L-VLPFC ($t(14) = 2.533$, $p < 0.05$) was greater during completion of the flow state scale after the experimental task than during completion of the flow state scale before the experimental task in the boredom condition (Fig. 2D).

Discussion

The present study used fNIRS to examine activity in the PFC during flow experienced under natural conditions. Brain activity was evaluated in two situations (during performance of the experimental task and when completing the flow state scale) and under two conditions (flow and boredom). The flow state scale score was higher in the flow condition than in the boredom condition, and we are confident that participants experienced psychological states of flow and boredom.

Because flow state is affected by proficiency, motivation and interest for a task [2], not all individuals will enter a flow state for a given task. In this study we excluded three participants because of an absence of flow state. The participants were excluded based on clear criteria using the flow state scale that has good reliability and validity, and we do not believe that exclusion of these participants introduced participation bias.

Activation of the R- and L-VLPFC was greater during the final 30 s of the experimental task (210–240 s) than throughout the entire experimental task (0–240 s) under flow conditions. In the current study, both the inferior frontal gyrus and the lateral orbitofrontal gyrus were included in the VLPFC. The lateral orbitofrontal gyrus is part of the orbitofrontal cortex and is involved in processing reward and emotions such as sympathy [22] and monitoring punishment, which is a self-evaluation process used to analyze changes in ongoing behavior [13]. Activation of the R- and L-VLPFC during the experimental task under flow conditions may therefore suggest that these areas are involved in processing reward and emotion in a state of flow.

There was no significant change in oxy-Hb concentration in the FPA and DLPFC during the final 30 s of task performance in the flow condition. Task-related decreases in activity (regional cerebral blood flow and blood-oxygen-level-dependent signal) are commonly observed in the PFC when participants are playing a video game [23]. A meta-analysis of nine PET studies by Shulman et al. [24] suggested that regional cerebral blood flow in the medial frontal region running along a dorsal-ventral axis (Brodmann areas 8, 9, 10, and 32) consistently decreased during performance of nine goal-directed tasks. Additionally, an fMRI study using a visual task [25] demonstrated a negative correlation between the load of sustained attention (vigilance) toward visual stimuli and activity of the dorsal medial PFC (Brodmann areas 9 and 10), indicating that increased attention to visual stimuli was associated with decreased blood-oxygen-level-dependent signal in medial frontal regions. Therefore, increases in attention when performing a game task under flow conditions might not increase activation of the FPA and DLPFC. On the other hand, oxy-Hb concentration during the experimental task decreased dramatically in all ROIs in the boredom condition. These changes were obviously different from those observed in the flow task, and might be caused by low task difficulty.

We measured the brain activity when participants were completing the flow state scale to evaluate brain activity that was not confounded by motor-related and task-specific brain activity. Several studies on memory retrieval have suggested that there is a reactivation of cortical regions during encoding, such that visual-, auditory- or content-specific areas reactivate for visual-, auditory- or content-specific memories [26, 27]. When completing the flow state scale after performing the task, participants were required to recall or retrieve their cognitive and psychological state during the video game task, and the brain activity during completion of the scale should therefore reflect the psychological state during the task. In the flow condition, activation of extensive areas of the PFC was greater when participants were completing the post-task flow state scale than when they were completing the pre-task flow state scale. Gray et al. [28] reported that the lateral PFC was the main cerebral region that was active in response to the interaction between a memory task and the emotional valence of a stimulus. The left hemisphere is highly involved in processing positive emotions [29] and the right hemisphere may be involved in processing negative emotions, although the results are somewhat equivocal [30]. Activity in the L-DLPFC was higher when participants were completing the post-task flow state scale than when they were completing the pre-task flow state scale in the flow condition, but not in the boredom condition. Flow is thought to be associated with positive emotions; therefore, this might represent activation of brain areas related to recall or retrieval of the positive emotional experience in the flow condition.

In the flow condition, activation of the L- and R-FPA was greater when participants were completing the post-task flow state scale than when they were completing the pre-task flow state scale. The FPA plays an important role in multitasking, particularly in the selection and maintenance of high-order internal goals during the performance of sub goals [11,12]. The bilateral activation of the FPA during completion of the post-task flow state scale in the flow condition might indicate that participants maintained or selected a high-order internal goal while they performed the video game task.

There was a significant increase in oxy-Hb concentration in the L-and R-VLPFC in the boredom condition and in the L-VLPFC in the flow condition. These areas are related to monitoring reward and emotional processing [13], but are also related to cognitive control of memory in retrieval and recall [31]. In this case, we speculate that the VLPFC was involved in the cognitive control of memory, because activation was observed in both the boredom and the flow conditions.

In contrast to a previous study [7], we observed no significant activation of premotor or supplementary motor areas. Activation of these areas is probably not essential for flow, but may be induced by task characteristics. In support of this interpretation, flow can be experienced in tasks such as chess [3], which have few motor requirements.

Three limitations of the present study should be noted. First, fNIRS has low spatial resolution and cannot be used to evaluate activity deep inside the brain. Previous studies have reported that the striatum, the reward system in the midbrain, and the anterior cingulate cortex are active during flow, but we were not able to determine the involvement of those areas in the present study. Second, there may be some minor deviation of optode positions because of individual differences of head size. However, we thought the problem was minor because the ROIs were close to the reference point (Fpz) (Fig.1). Third, we used a computer video game task to induce flow state because it is easy to control the difficulty of the task. However, the deactivation of the DLPFC and FPA observed during task performance in the flow condition may be specific to video games, as task-related decreases in activity in these regions are commonly observed during video game play [23]. As such, the results of this study may not be generalizable to other tasks, and future studies should examine brain activity during flow in other tasks.

To our knowledge, this is the first study that has employed fNIRS to evaluate brain activity during the flow state, allowing the flow state to be created in a natural and comfortable environment. The results suggest that flow is associated with activity of the PFC, and may therefore be associated with functions such as cognition, emotion, maintenance of internal goals, and reward processing. These findings are consistent with flow theory [2,3] and the results of this study make an important contribution to our understanding of brain activity during flow.

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Fig. 1. Illuminators are shown as white squares and detectors are shown as gray squares. Channels are shown as black circles. The positions of the optodes are shown as red dots. Fpz is based on the international 10-20 system. Yellow, green, and blue frames show the frontal pole area, dorsolateral prefrontal cortex area, and ventrolateral prefrontal cortex area, respectively.

Fig. 2. Panels A and C show the average change in oxy-Hb concentration throughout the entire 4-min experimental task (0–240 s; light gray) and the final 30-s of the experimental task (210–240 s; dark gray). Panels B and D show the average change in oxy-Hb concentration when completing the flow state scale before (light gray) and after (dark gray) performing the experimental task. * $p < 0.05$, ** $p < 0.01$. Error bars indicate standard error.

Fig 1.

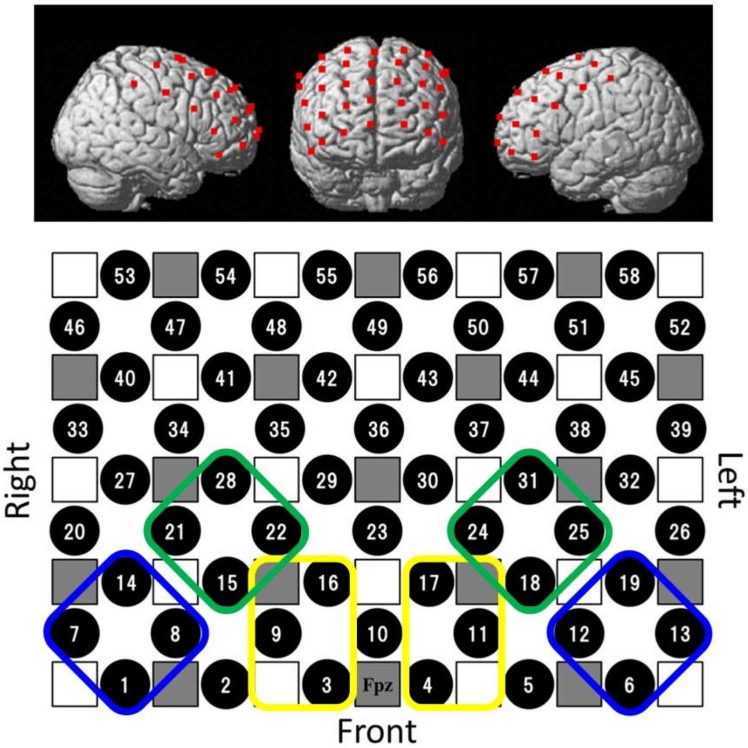
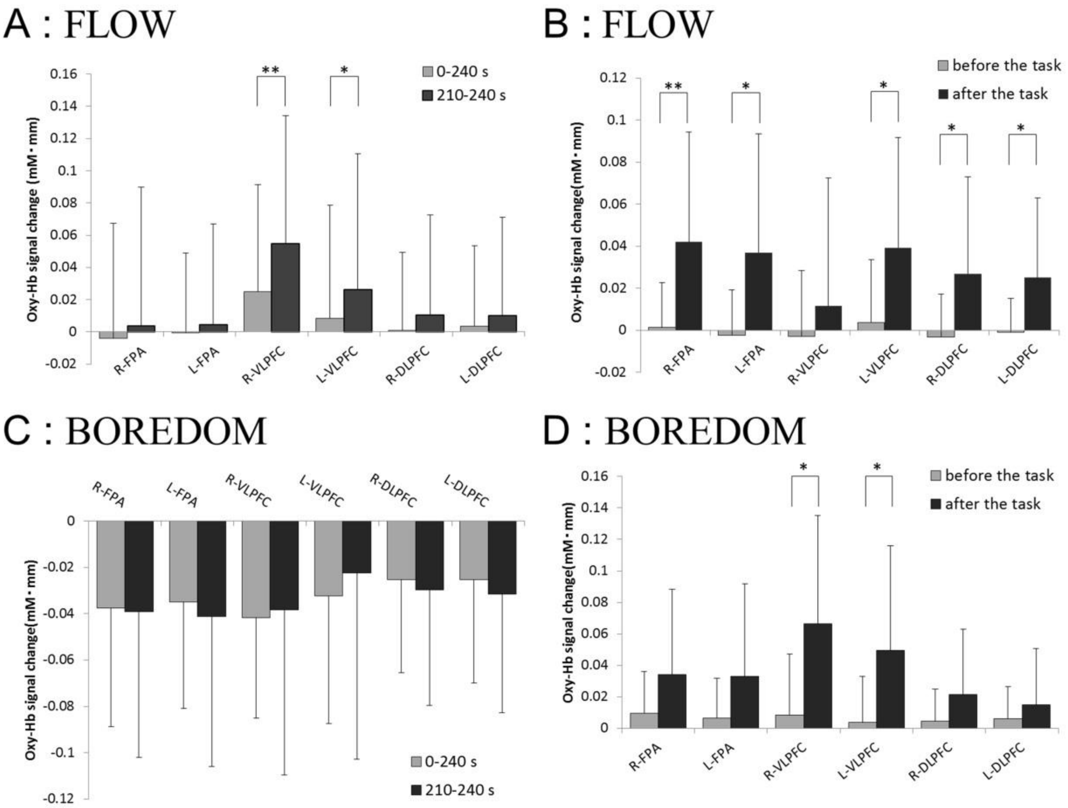

53 54 55 56 57 58
46 47 48 49 50 51 52
40 41 42 43 44 45
33 34 35 36 37 38 39
27 28 29 30 31 32
20 21 22 23 24 25 26
14 15 16 17 18 19
7 8 9 10 11 12 13
1 2 3 Fpz 4 5 6
Right
Left
Front

Fig 2.



A : FLOW
0-240 s
210-240 s
Oxy-Hb signal change (mM・mm)
R-FPA
L-FPA
R-VLPFC
L-VLPFC
R-DLPFC
L-DLPFC
B : FLOW
before the task
after the task
Oxy-Hb signal change(mM・mm)
C : BOREDOM
D : BOREDOM