Psychophysiology, 48 (2011), 1562–1570. Wiley Periodicals, Inc. Printed in the USA.

DOI: 10.1111/j.1469-8986.2011.01220.x

Prefrontal overactivation, autonomic arousal, and task performance under evaluative pressure: A near-infrared spectroscopy (NIRS) study

HIROYUKI ITO,[a] HOSHIKO YAMAUCHI,[b] HITOSHI KANEKO,[c] TORU YOSHIKAWA,[d] KENJI NOMURA,[c] AND SHUJI HONJO[c,d]

[a]Osaka-Hamamatsu Joint Center for Child Development, Hamamatsu University School of Medicine, Hamamatsu, Japan
[b]Center for Student Counseling, Nagoya University, Nagoya, Japan
[c]Center for Developmental Clinical Psychology and Psychiatry, Nagoya University, Nagoya, Japan
[d]Department of Psychiatry for Parents and Children, Nagoya University Hospital, Nagoya, Japan

Abstract

To study the mechanism underlying the influence of psychological pressure on task performance, we investigated the relationship between prefrontal activation, autonomic arousal, and performance in an *n*-back working memory task with 3 load levels (l-, 2-, and 3-back tasks) under evaluative pressure. The tasks were performed by 32 university students with or without evaluative observation by experimenters. The error rate and prefrontal activation were found to increase with pressure only in the highest load task (3-back). In contrast, autonomic arousal increased with pressure regardless of the task condition. Correlation analysis showed a positive correlation of the error rate with prefrontal activation in the 3-back task and no consistent correlation with autonomic arousal. We concluded that the inhibitory effect of evaluative pressure on task performance is mediated by prefrontal overactivation rather than autonomic arousal.

Descriptors: Normal volunteers, Heart rate, Electrodermal, Anxiety

Pressure to perform well sometimes paradoxically hampers performance. Researchers are investigating this phenomenon from various psychological viewpoints—social facilitation and inhibition, test anxiety, and choking under pressure. These studies have demonstrated that pressure improves performance in simple tasks such as vigilance, letter cancellation, and simple arithmetic but inhibits performance in complex tasks including recognition, recall, and memory scanning (see review of Geen & Gange, 1977; meta-analysis of Bond & Titus, 1983). Humphreys and Revelle (1984) reviewed these works and concluded that the effect of pressure is determined by the working memory (WM) load of the task. That is, the extent by which pressure inhibits performance is greater in higher WM load tasks than in lower WM load tasks. Additionally, Cottrell (1972) found that the effect of pressure was more intense when the pressure involved apprehension toward evaluation.

Despite all this investigation, the mechanism underlying the inhibitory effect of pressure on task performance is not clearly understood. There are two prominent explanations for this effect. Arousal theories suggest a motivation-based explanation: the pressure-induced decrease in performance is mediated by excessive drive or arousal (Cottrell, 1972; Humphreys & Revelle, 1984; Zajonc, 1965). These theories predict that the performance drop is associated with the activities of the autonomic nervous system (ANS), which are representative indices of arousal. However, in most previous studies on arousal theories, arousal has been operationally defined by experimental manipulations such as incentive or the presence of others, and few studies have measured actual physiological arousal. Even among studies that measured arousal, almost none investigated the direct relationship between physiological arousal and task performance. Thus, there is still no clear evidence showing that pressure-induced arousal mediates the decrease in task performance. In the present study, we measured ANS arousal during tasks and analyzed its relationship with task performance.

On the other hand, the attentional-distraction theory (Landers, 1980; Nideffer, 1992) and explicit-monitoring theory (Beilock & Carr, 2001; Lewis & Linder, 1997; Masters, 1992) suggest a cognition-based explanation for the pressure-induced drop in task performance: pressure to perform at optimal levels causes top-down interference, which consumes WM or interrupts proceduralized routines. When humans execute complex tasks under strong pressure, they often exhibit cognitive confusion and, in extreme cases, experience the mind "going blank." Considering

We thank Ippeita Dan and Daisuke Tsuzuki for providing coordinate data of brain surface corresponding to NIRS channels. We also thank Hiroko Yamamoto for drawing an illustration of the instrumental setting for measurement.

Address correspondence to: Hiroyuki Ito, Osaka-Hamamatsu Joint Center for Child Development, Hamamatsu University School of Medicine, 1-20-1, Handayama, Higashi-ku, Hamamatsu, 431-3192, Japan. E-mail: ito_h@hama-med.ac.jp

PSYCHOPHYSIOLOGY

that this phenomenon includes disturbance of cognitive processing, expression can reasonably be assumed to comprise changes in the brain cortex; particularly the prefrontal areas that are responsible for cognitive control (Miller & Cohen, 2001). However, almost no studies have investigated the relationship between prefrontal activation and task performance under pressure. In the present study, prefrontal activity was measured using near-infrared spectroscopy (NIRS) during the execution of a task under pressure, and the relationship between prefrontal activity and task performance was examined.

Like functional magnetic resonance imaging (fMRI), NIRS is a hemodynamically based technique that measures activity in the human cortex. NIRS noninvasively measures changes of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb), which are then interpreted as indicators of cortical activation. Using NIRS measurements, neural activation is typically expressed as an increase in oxy-Hb and a decrease in deoxy-Hb (Hirth et al., 1996; Hock et al., 1995; Hoshi & Tamura, 1993; Obrig et al., 2000; Villringer, Planck, Hock, Schleinkofer, & Dirnagl, 1993; Watanabe & Kato, 2004). Unlike fMRI or positron emission tomography (PET), NIRS cannot measure deep brain structures and also has a relatively low spatial resolution of 20–30 mm. However, its advantages include being noninvasive, allowing easy measurement and being relatively resistant to motion artifacts (Miyai et al., 2001). Furthermore, NIRS enables measurements in less restricted and noisy conditions (Okamoto et al., 2004). This advantage is particularly important in the present study, which uses the easily influenced social factor of evaluative observation. Although it has been suggested that NIRS signals reflect not only cerebral hemodynamics but scalp and facial blood flow in adults, several studies have demonstrated strong correlations between NIRS signals and cerebral activation measured by fMRI (Huppert, Hoge, Diamond, Franceschini, & Boas, 2006) or PET (Hock et al., 1997).

ANS activity was measured using fingertip sensors so that these noninvasive measurements could also be made in a natural setting. Skin temperature, skin conductance level (SCL), heart rate, and blood volume pulse (BVP) amplitude were measured as indicators of ANS arousal. As autonomic arousal is defined as the predominance of sympathetic nervous system activity, it is shown as elevations in SCL and heart rate and decreases in skin temperature and BVP amplitude.

In sum, we investigated the relationship between task performance and prefrontal and ANS activity recorded when subjects performed a WM task under pressure, whereby evaluation apprehension was elicited. According to the motivation-based hypothesis, performance decrement under pressure is positively related to ANS activity while, according to the cognition-based hypothesis, it is positively related to prefrontal activation.

Methods

Participants

Participants comprised 32 healthy undergraduate students with a mean age of 18.8 years ($SD = 1.4$). The participants were randomly assigned to either a pressure group ($n = 17$) or a control group ($n = 15$). All participants were right-handed (assessed by the Edinburgh Handedness Inventory of Oldfield, 1971) and had normal visual acuity.

Written informed consent was obtained from all the participants. The protocol of this study was approved by the ethics committee of the Nagoya University Graduate School of Education and Human Development (receipt number: PR10-33).

Experimental Design

The experiment employed a 2 × 3 factorial design (pressure and WM load of task). Pressure was a between-subjects factor and WM load was a within-subjects factor. Task performance (error rate and reaction time), ANS indicators (heart rate, BVP amplitude, SCL, and skin temperature), and NIRS signal (oxy-Hb and deoxy-Hb) were established as dependent variables.

Procedure

Upon entering the test room, participants first received the experimental explanation, completed the consent form, and then were seated at a desk with a computer. We explained the experimental tasks to the participants, and, for approximately one-third the length of the actual trials, they practiced all the tasks in the same form as the actual trials but with different content (i.e., sequence of letters). Once understanding was confirmed, an NIRS probe and ANS fingertip sensor were attached (Figure 1). The signals were then confirmed, followed by a 2.5-min rest period. After the rest period, pressure instruction (detailed below) was given to participants in the pressure group. Then the tasks were started. A block design was used consisting of task blocks in 3 load conditions (1-back, 2-back, and 3-back). Each task block was preceded by a control block to measure baseline prefrontal activity. The order of the task blocks was counterbalanced between the participants.

Manipulation of Pressure

Participants in the pressure group were told that their task performance would be compared with that of other university

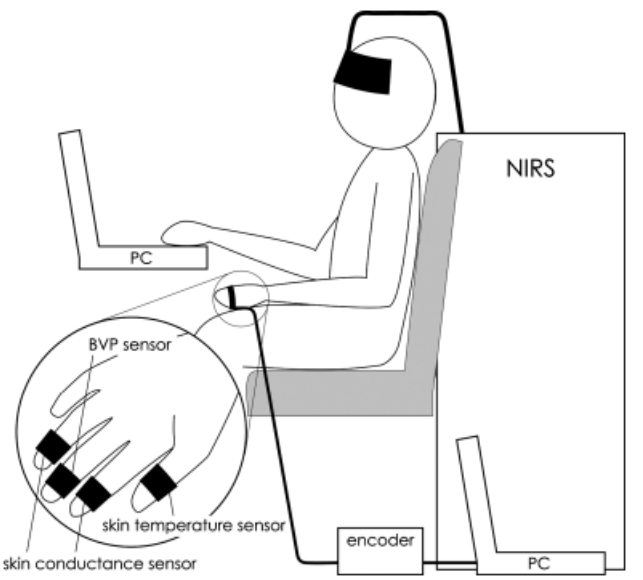

Figure 1. Instrumental setting for NIRS and ANS measurements. NIRS = near-infrared spectroscopy, BVP = blood volume pulse, ANS = autonomic nervous system.

students, and that, depending on their ranking, they would receive an incentive of up to 500 Japanese yen, in addition to the 1000 yen compensation for participating in the experiment. Participants were also told that two experimenters would monitor the correctness and speed of their responses during the tasks while standing behind them in order to "score them quickly." One of the experimenters (male) stood approximately 50 cm behind and to the left of the participant, monitoring them while holding a clipboard and pen. Another experimenter (female) monitored the participant from a desk with a computer, about 1 m behind and to the right of them.

The above instructions and observations were not conducted with the control group. While control group participants were performing tasks, the experimenters moved behind a partition so that they would be out of the participants' eyesight.

N-Back Task

During the control block, the words "Yes" or "No" were alternately displayed on the screen for 2000 ms with a 500-ms interstimulus interval (ISI; the interval between the offset of one stimulus and the onset of the following stimulus). When the word "Yes" was displayed, the participant was required to press the "yes" key (the "1" key on the numerical keypad), which was indicated by a white sticker, as quickly as possible; when the word "No" was displayed, the participant pressed the "no" key (the "3" key on the numerical keypad), indicated by a black sticker. When the 50-s control block was finished, brief instruction on the subsequent *n*-back task was displayed; for example, "Compare with 3 letters back." There was a 5-s countdown and a blank screen was shown for 500 ms before each task block was implemented.

In each block, one of the three versions of the letter *n*-back was conducted. In the 1-back condition, participants were instructed to press, as quickly as possible, the "yes" key if the letter displayed was the same as that displayed on the immediately preceding screen, and "no" if it was different. Similarly, participants were required to compare letters with those displayed two screens previously in the 2-back condition, and with those displayed three screens previously in the 3-back condition. However, no response was required in the first screen in the 1-back condition, the first two screens in the 2-back condition, and the first three screens in the 3 back-condition because judgment was impossible. Four letters were used: "A," "B," "C," and "D." The letters were presented in pseudo-randomized order for 2000 ms with a 500-ms ISI. A total of 24 screens required a response in all of the conditions. The task times for the three conditions were therefore 62.5 s (1-back), 65 s (2-back), and 67.5 s (3-back). In all of the tasks, stimulus sequences were prepared so that an equal number of "yes" and "no" responses were correct. All responses in the control and task blocks were performed using the right hand (the dominant hand), because the ANS activity sensors were attached to the left hand. Because the participants required almost the same motion with the same hand for the control and task blocks, the influence of behavioral motion on cerebral activity would have been negated.

Both the keys pressed and the reaction times were recorded, and the error rate and mean reaction time were calculated for each participant and task condition. The error rate was calculated as the mean for the 24 trials of each task, with a correct response represented by 0, no response by 0.5 (chance level), and error response by 1. Reaction times were averaged for each task using the reaction times of trials in which a response was made, and did not include trials for which no response was given.

NIRS

The principles of NIRS measurements have been described in detail by Hoshi (2003), Obrig and Villringer (2003), and others. Measurements were made using a continuous wave system (ETG-4000, Hitachi Medical Co., Japan) with a 3×5 probe set. This probe set is constructed of 7 photodetectors and 8 illuminators (wavelengths are 695 ± 20 nm and 830 ± 20 nm), and is 6×12 cm in size (probe interval is 3 cm). As NIRS channels are defined as the midpoint of the neighboring detector-illuminator pairs, the number of channels in this probe set is 22. The probe set was attached to the front of the participant's head. Specifically, the bottom central probe was positioned at Fpz of the international 10–20 method (Jasper, 1958). The brain areas corresponding with the 22 channels are shown in Figure 2. The sampling rate was set at 10 Hz. The participants were instructed to move their head as little as possible and were filmed from behind during the measurement. Later, we checked the recorded images together with the NIRS signals and confirmed that no salient head motion entailing a significant artifact was observed.

Hemoglobin concentration data (oxy-Hb and deoxy-Hb) in the channel with low signal to noise (S/N) ratios were excluded for each participant when their standard deviations during the rest period were greater than 1 mmol $\times$ mm after processing of the 5-s moving average. Channels #15, #16, #17, #19, #20, #21, and #22, which were positioned higher, included much of the data with low S/N ratios due to hair. Since data from these channels were excluded in more than 20% of participants, the data from these channels in all participants were not used in the subsequent analysis. Of the data for the remaining 15 channels across the 32 subjects, the number of data excluded was 25 (5.21%). On the basis of virtual spatial registration (Singh, Okamoto, Dan, Jurcak, & Dan, 2005; Tsuzuki et al., 2007) and 3-D

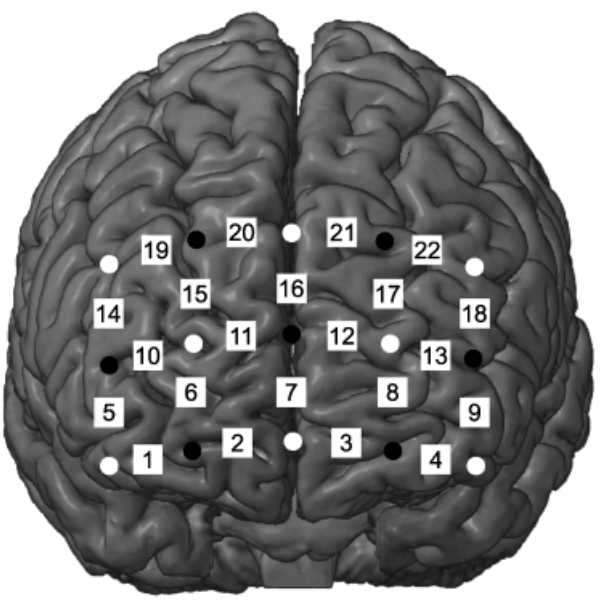

Figure 2. Arrangement of the NIRS channels on a standard brain surface. Photo-detectors are shown as black circles, illuminators as white circles, and channels as squares. NIRS = near-infrared spectroscopy.

digital Talairach Atlas (Lancaster et al., 2000), we can infer that the regions measured in this study correspond to the frontopolar cortex and a part of the dorsolateral prefrontal cortex (Brodmann area 10 and 46, respectively).

From the findings from earlier studies that stress produces bilaterally asymmetrical prefrontal activity (Tanida, Katsuyama, & Sakatani, 2007; Tanida, Sakatani, Takano, & Tagai, 2004), the seven channels placed over the right hemisphere (#1, #2, #5, #6, #10, #11, and #14) were determined to be first region of interest (ROI 1) and the seven channels placed over the left hemisphere (#3, #4, #8, #9, #12, #13, and #18) to be second region of interest (ROI 2). Relative concentrations of both oxy-Hb and deoxy-Hb were calculated by subtracting the mean values during the final 30 s of the control block from the mean values during the task block and then averaged across the seven channels in each ROI for each participant and task condition. These relative data were used in the statistical analysis.

ANS Activity

The methods of ANS data collection and analysis used in this study are in line with the guidelines published by *Psychophysiology* (Fowles et al., 1981; Jennings et al., 1981). ANS activity was measured and recorded noninvasively using a multimodality encoder system (ProComp5 Infiniti, Thought Technology Ltd.) and software program (BioGraph Infinity, Thought Technology Ltd.). Three types of sensors were attached to the first joints of the thumb and three fingers of each participant's left hand. Specifically, a BVP sensor (photoplethysmograph for assessing heart rate and BVP amplitude) was attached to the middle finger, a skin conductance sensor to the index finger and annular finger, and a skin temperature sensor to the thumb (Figure 1). The sampling rate was set at 256 Hz for BVP and 16 Hz for SC and skin temperature. Participants were instructed not to move the left hand during measurements, and to place it palm up on their leg.

Relative values for heart rate, SCL, and skin temperature were calculated by subtracting the mean value during the final 90 s of the resting period from the mean value during the task block for each participant and task condition. For BVP amplitude, the percentile value was calculated by dividing the mean value during the task block by the mean value during the final 90 s of the rest period and multiplying by 100 for each participant and task condition. These relative data were used in the statistical analysis.

As mentioned above, a 30-s baseline interval was set at the end of the control block for NIRS measures, while a 90-s baseline was set at the end of the resting period for ANS measures. This was due to the intrinsic differences in the NIRS and ANS measures. NIRS data are represented in relative rather than absolute values and are susceptible to changes due to signal drift induced by physical factors unrelated to brain activity, such as changes in the participants' posture or shift of probe position. Furthermore, NIRS data obtained from the prefrontal area is subject to task-related but unessential perceptual and motor processing such as simply perceiving displayed letters and intending to press the keys. For these reasons, a control task should be performed to obtain baseline NIRS data in the interval between the experimental tasks. On the other hand, in the case of ANS measures, such a drift due to physical factors is less likely to occur. Instead, ANS measures are considerably influenced by subtle emotional changes in the participants. Therefore, to minimize random error for ANS activity measurement, a longer resting interval is necessary to obtain the baseline measures when the participants are in a relaxed state rather than iteratively in the midst of the experiment where various emotions can occur such as anxiety, disappointment, or sense of achievement. In view of these points, different baseline intervals were set for NIRS measures and ANS measures in this study.

Statistical Analysis

For all data, analysis of variance (ANOVA) was conducted with the presence or absence of pressure as a between-participants factor and task condition (1-back, 2-back, and 3-back) as a within-participants factor. The Huynh-Feldt correction was applied to address violations of the sphericity assumption. As post-hoc analyses following significant interactions, we calculated the simple main effects of pressure in each task condition and interaction contrast as the difference in the effect of pressure between the task conditions. The effect sizes (partial eta squared) were calculated together with the significance probability (two-tailed). In addition, the effect sizes d (Cohen, 1988) were calculated as the difference of the mean values of the pressure condition and the control condition divided by the mean standard deviation of the two conditions. For NIRS data, the mean value of d for both oxy-Hb and deoxy-Hb in ROI 1 and ROI 2 (positive and negative are reversed for deoxy-Hb) were calculated. For ANS data, the mean value of d for the four ANS measures (positive and negative are reversed for skin temperature and BVP) were calculated. This approach is advantageous especially for NIRS data, because effect sizes eliminate the bias of differential path-length factors (DPFs), which exhibit inter- and intraindividual variation and were not measured in the current study (Schroeter et al., 2004).

Furthermore, for the task conditions wherein pressure-induced changes in behavioral performance were observed, Pearson's correlation coefficients were calculated for assessing the relationship of behavioral data with NIRS and ANS data. We also determined the correlation between the NIRS and ANS data to examine the possibility that the NIRS signals were influenced by facial blood flow regulated by ANS (Drummond, 1999). If the NIRS signals are affected by facial blood flow, they should show correlation with ANS measures. SPSS 10.0.7J (SPSS Inc.) was used for all statistical analyses.

Results

Behavioral Data

The mean values for error rate and reaction time in each condition are shown in Table 1, and the results of ANOVA are shown in Table 2. For error rate, an interaction between the two factors was significant. A post hoc analysis revealed that, in the 3-back condition, the error rate was significantly higher in the pressure group than in the control group, $F(1,30) = 4.49$, $p = .04$, $\eta p2 = .13$. In the 1-back and 2-back conditions, the simple main effect of pressure was not significant, $F(1,30) = 1.09$, $p = .30$, $\eta p2 = .04$, and $F(1,30) = .62$, $p = .44$, $\eta p2 = .02$, respectively. The interaction contrast of 1-back versus 2-back was not significant, $F(1,30) = 1.35$, $p = .26$, $\eta p2 = .04$, but that of 1-back and 2-back versus 3-back was significant, $F(1,30) = 4.37$, $p = .05$, $\eta p2 = .13$, indicating that the increase in the error rate due to pressure was higher in the 3-back task than in the other tasks.

For reaction time, only the main effect of task was significant (1-back $<$ 2-back, $p < .01$; 1-back and 2-back $<$ 3-back,

Table 1. *Mean Value and Standard Deviation of Each Variable in Each Condition*

	1-back				2-back				3-back			
	Control		Pressure		Control		Pressure		Control		Pressure	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Behavioral data												
Error rate (%)	3.06	3.68	1.96	2.14	3.47	4.29	4.90	5.80	16.11	11.34	25.86	14.25
Reaction time (ms)	572	112	579	123	744	236	802	229	921	256	1035	228
NIRS data												
Oxy-Hb in ROI 1	−.01	.06	−.03	.18	.00	.11	.09	.21	−.03	.19	.26	.31
Oxy-Hb in ROI 2	.01	.10	−.06	.30	.00	.12	.12	.28	−.05	.19	.30	.33
Deoxy-Hb in ROI 1	−.01	.04	−.01	.05	−.04	.05	−.05	.07	−.04	.06	−.09	.07
Deoxy-Hb in ROI 2	−.02	.03	.00	.05	−.03	.04	−.04	.07	−.02	.06	−.06	.07
ANS data												
Skin temperature (°C)	−.11	.34	−.33	.49	−.09	.25	−.33	.47	−.13	.24	−.46	.45
SCL (μS)	1.91	1.46	3.17	1.64	2.36	2.01	3.46	1.96	2.49	1.93	3.34	1.70
Heart rate (bpm)	.96	4.72	3.65	6.58	3.91	4.25	10.38	10.78	4.76	7.10	8.13	9.89
BVP amplitude (%)	76.78	16.67	62.29	20.14	65.32	21.31	46.43	21.38	62.42	22.01	45.22	23.10

Note. The values for NIRS data and ANS data are relative values. ROI 1 and ROI 2 were placed over the right and left prefrontal cortex, respectively. *M* = mean, *SD* = standard deviation, NIRS = near-infrared spectroscopy, ROI = region of interest, Oxy-Hb = oxygenated hemoglobin, Deoxy-Hb = deoxygenated hemoglobin, ANS = autonomic nervous system, SCL = skin conductance level, BVP = blood volume pulse.

$p < .01$). The main effect of pressure and interaction between the two factors were not significant.

NIRS Data

The mean values for relative concentrations of oxy-Hb and deoxy-Hb for each ROI and condition are shown in Table 1, and the results of ANOVAs are shown in Table 2. Since NIRS data obtained by the instrument for continuous wave measurements are subject to the optical path length, it is difficult to directly compare the activity levels in different brain areas (Hoshi, 2005). Therefore, ROI was not included as an independent variable in ANOVAs.

A significant interaction was observed with oxy-Hb in ROI 1 (right prefrontal area). A post hoc test revealed that, in the 3-back condition, the pressure group showed significantly higher activation than the control group, $F(1,30) = 9.86$, $p < .01$, $\eta p2 = .25$. In the 1-back and 2-back conditions, the simple main effect of pressure was not significant, $F(1,30) = .10$, $p = .75$, $\eta p2 = .00$, and $F(1,30) = 2.66$, $p = .11$, $\eta p2 = .08$, respectively. The interaction contrast of 1-back versus 2-back was not significant, $F(1,30) = 2.47$, $p = .13$, $\eta p2 = .08$, but that of 1-back and 2-back versus 3-back was significant, $F(1,30) = 5.07$, $p = .03$, $\eta p2 = .14$. For oxy-Hb in ROI 2 (left prefrontal area), the interaction was also significant and the same results were seen in the tests of simple effects, 1-back: $F(1,30) = .75$, $p = .39$, $\eta p2 = .03$; 2-back: $F(1,30) = 2.54$, $p = .12$, $\eta p2 = .08$; 3-back: $F(1,30) = 13.65$, $p < .01$, $\eta p2 = .31$. The interaction contrast of 1-back versus 2-back and that of 1-back and 2-back versus 3-back were significant, $F(1,30) = 4.46$, $p = .04$, $\eta p2 = .13$ and $F(1,30) = 6.09$, $p = .02$, $\eta p2 = .17$, respectively.

For deoxy-Hb, a significant interaction was observed, and the tests of simple effects demonstrated similar results as those obtained for oxy-Hb both in ROI 1, 1-back: $F(1,30) = .03$, $p = .87$, $\eta p2 = .00$; 2-back: $F(1,30) = .11$, $p = .74$, $\eta p2 = .00$; 3-back: $F(1,30) = 5.48$, $p = .03$, $\eta p2 = .15$, and ROI 2, 1-back: $F(1,30) = 1.82$, $p = .19$, $\eta p2 = .06$; 2-back: $F(1,30) = .17$, $p = .69$, $\eta p2 = .00$; 3-back: $F(1,30) = 3.25$, $p = .08$, $\eta p2 = .10$. The interaction contrasts of 1-back versus 2-back was not

Table 2. *Result of Two-Way (Pressure × Task) ANOVA for Each Dependent Variable*

	Pressure				Task				Interaction			
	F	*df*	*p*	ηp2	*F*	*df*	*p*	ηp2	*F*	*df*	*p*	ηp2
Behavioral data												
Error rate	3.68	1, 30	.07	.11	51.04	1.4, 42.3	<.01	.63	3.93	1.4, 42.3	.04	.12
Reaction time	.92	1, 30	.35	.03	79.26	2, 60	<.01	.73	1.40	2, 60	.25	.05
NIRS data												
Oxy-Hb (ROI 1)	12.31	1, 30	<.01	.29	3.10	1.7, 50.5	.06	.09	4.43	1.7, 50.5	.02	.13
Oxy-Hb (ROI 2)	9.90	1, 30	<.01	.25	2.95	1.7, 51.7	.07	.09	5.67	1.7, 51.7	<.01	.16
Deoxy-Hb (ROI 1)	1.83	1, 30	.19	.06	9.14	2, 60	<.01	.23	3.19	2, 60	.05	.10
Deoxy-Hb (ROI 2)	.44	1, 30	.55	.01	2.69	2, 60	.08	.02	3.17	2, 60	.05	.10
ANS data												
Skin temperature	4.14	1, 30	.05	.12	1.95	2, 59.7	.15	.06	0.85	2, 59.7	.43	.03
SCL	3.09	1, 30	.09	.09	3.84	1.8, 54.6	.03	.11	0.86	1.8, 54.6	.43	.03
Heart rate	2.86	1, 30	.10	.09	12.92	2, 59.2	<.01	.30	1.91	2, 59.2	.16	.06
BVP amplitude	6.31	1, 30	.02	.17	19.73	2, 58.6	<.01	.40	0.33	2, 58.6	.72	.01

Note. ROI 1 and ROI 2 were placed over the right and left prefrontal cortex, respectively. NIRS = near-infrared spectroscopy, ROI = region of interest, Oxy-Hb = oxygenated hemoglobin, Deoxy-Hb = deoxygenated hemoglobin, SCL = skin conductance level, BVP = blood volume pulse.

significant both in ROI 1, $F(1,30) = 0.17$, $p = .68$, $\eta p2 = .01$, and ROI 2, $F(1,30) = 1.57$, $p = .22$, $\eta p2 = .05$, but that of 1-back and 2-back versus 3-back was significant both in ROI 1, $F(1,30) = 5.69$, $p = .02$, $\eta p2 = .16$, and ROI 2, $F(1,30) = 4.55$, $p = .04$, $\eta p2 = .13$. These results for NIRS data were similar to the results for error rate. To illustrate this clearly, effect sizes d of pressure on NIRS data are shown in Figure 3 together with those on error rate for each task condition. A positive d indicates that pressure heightened each dependent variable (error rate, prefrontal activation, ANS arousal). As demonstrated in Figure 3, prefrontal activation shows a pattern similar to that of error rate.

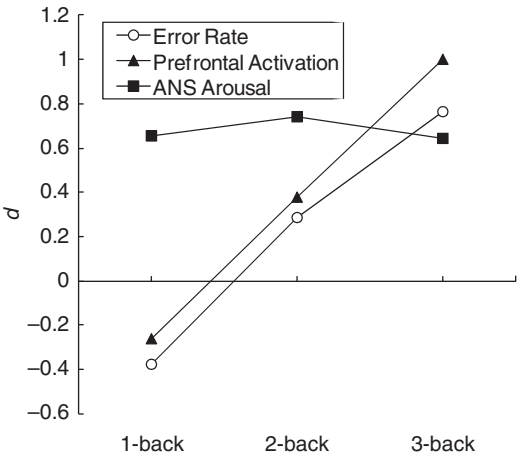

Figure 3. The effect sizes d of pressure on error rate, prefrontal activation, and ANS arousal for each task condition. The mean values of d for both oxy-Hb and deoxy-Hb in ROI 1 and ROI 2 (the positive and negative values are reversed for deoxy-Hb) are plotted as "Prefrontal Activation." The mean values of d for the 4 ANS measures (the positive and negative values are reversed for skin temperature and BVP) are plotted as "ANS Arousal." ROI = region of interest, Oxy-Hb = oxygenated hemoglobin, Deoxy-Hb = deoxygenated hemoglobin, ANS = autonomic nervous system, BVP = blood volume pulse.

ANS Data

The mean values for the four ANS indicators under each condition are shown in Table 1, and the results of ANOVA are shown in Table 2. There was no significant interaction effect with any of the indicators. The main effects of pressure on skin temperature and BVP amplitude were significant, indicating that the pressure group showed higher arousal than the control group. The main effects of task on SCL, heart rate, and BVP amplitude were significant. In multiple comparison with the Bonferroni method, heart rate and BVP amplitude showed significantly higher arousal in 2-back and 3-back than in 1-back ($ps < .01$).

These results differ from the results for behavioral performance and prefrontal activation. As shown in Figure 3, ANS arousal, unlike error rate and prefrontal activation, is affected uniformly by pressure, regardless of task condition.

For comparison, the ANS activity was calculated with the same baseline set as that used for NIRS measurement; no significant interaction effect was observed for any of the indicators, which was also the case in the original analysis. Furthermore, the main effect of pressure and task, which was observed in the original analysis, disappeared because of substantial fluctuation in the baseline measures. This indicates that it is reasonable to establish different baseline intervals for ANS and NIRS measures for minimizing random errors.

Correlation Analysis

Pearson's correlation coefficients between the error rate and the NIRS and ANS data were calculated for the 3-back condition, wherein a pressure-induced increase in error rate was observed (Figure 4). For the NIRS data, oxy-Hb showed positive correlations with error rate, although the correlations were statistically significant only in ROI 2 (ROI 1: $r = .31$, $p = .08$, ROI 2: $r = .35$, $p = .05$). Deoxy-Hb showed similar correlations, although they were not statistically significant (ROI 1: $r = -.19$, $p = .31$, ROI 2: $r = -.26$, $p = .15$). For the ANS data, none of the indicators showed a significant correlation with the error rate (skin temperature: $r = -.02$, $p = .91$; SCL: $r = .10$, $p = .59$; heart rate: $r = .14$, $p = .44$; BVP amplitude: $r = -.01$, $p = .96$).

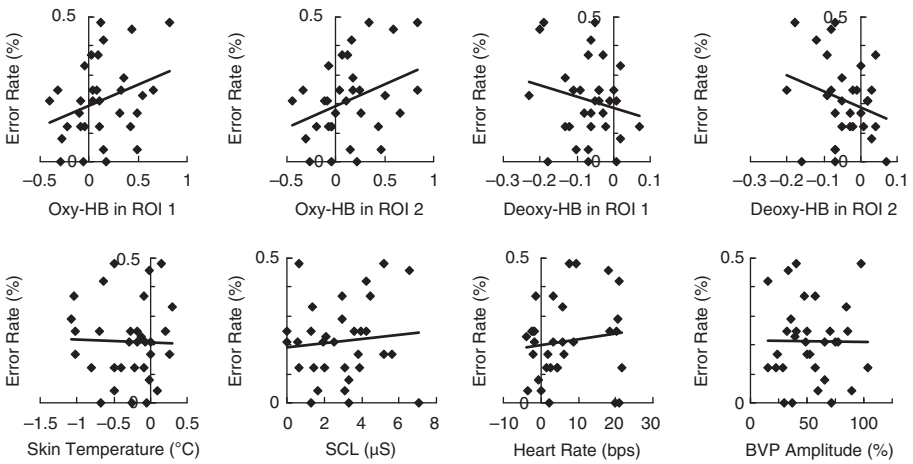

Figure 4. The relationship between error rates and NIRS (upper column) and ANS measures (lower column) in the 3-back task. A regression line is shown for each panel. ROI 1 and ROI 2 were placed over the right and left prefrontal cortex, respectively. NIRS = near-infrared spectroscopy, ROI = region of interest, Oxy-HB = oxygenated hemoglobin, Deoxy-HB = deoxygenated hemoglobin, ANS = autonomic nervous system, SCL = skin conductance level, BVP = blood volume pulse.

The correlation coefficients between the NIRS and ANS data for the 3-back condition are shown in Table 3. The intercorrelations of NIRS signals were strong. Similarly, comparatively clear intercorrelations of ANS measures were observed. As for the correlation between NIRS and ANS measures, deoxy-Hb showed moderate correlations with the ANS measures, especially with SCL and BVP amplitude. In contrast, oxy-Hb showed no significant correlation with the ANS data.

Discussion

For behavioral performance, an increase in the error rate with evaluative pressure was observed only in the 3-back task, which has the highest WM load. This result agrees with many earlier psychological findings (cf. Humphreys and Revelle, 1984). However, the ANS data indicated that pressure increased autonomic arousal uniformly in the 3 tasks. This pattern does not correspond with that of task performance (see Figure 3). Additionally, no consistent correlation between ANS indicators and task performance was observed in any of the 3 tasks. These results do not support the motivation-based hypothesis, including the arousal theories (Cottrell, 1972; Humphreys & Revelle, 1984; Zajonc, 1965).

In contrast, the NIRS data (oxy-Hb and deoxy-Hb) indicated that cortical activity in both the right and left prefrontal areas increased with evaluative pressure only in the 3-back task. This pattern corresponds closely with that of error rate (see Figure 3). In addition, the correlation analysis showed that oxy-Hb, a main NIRS indicator of cortical activity (Hoshi, 2005), was positively correlated with error rate in the 3-back task. Although deoxy-Hb showed moderate correlations with ANS measures, which indicated that deoxy-Hb partly reflects facial blood flow regulated by ANS, oxy-Hb showed no significant correlation with the ANS measures. This result corresponds to those of Takahama, Ohzawa, and Yoshikawa (2009), who demonstrated the relationship of facial blood flow with deoxy-Hb and not with oxy-Hb, and suggested that oxy-Hb is less influenced by facial blood flow as opposed to deoxy-Hb. Perhaps, this is because the changes in oxy-Hb are substantially greater in amplitude than the changes in deoxy-Hb and, consequently, any random and systematic errors, including facial blood flow, could disproportionately affect deoxy-Hb rather than oxy-Hb (Strangman, Culver, Thompson, & Boas, 2002). As described above, we found a clearer relation of behavioral data with oxy-Hb than with deoxy-Hb. This suggested that prefrontal activation reflected by oxy-Hb mediates performance decrement under pressure instead of ANS arousal reflected by ANS measures and deoxy-Hb. These results support the cognition-based hypothesis, including the attentional distraction theory (Landers, 1980; Nideffer, 1992) and explicit monitoring theory (Carver & Scheier, 1978; Jackson & Beilock, 2008). However, whether oxy-Hb is more specifically related to cognitive functions than deoxy-Hb is controversial (Cui, Bray, Bryant, Glover, & Reiss, 2011; Schroeter, Zysset, & von Cramon, 2004), and further studies are required on this issue.

Our results indicate that pressure-induced performance decrements are directly associated with changes in cognitive factors reflected by prefrontal activation, rather than changes in motivational and emotional factors such as anxiety and nervousness reflected by changes in ANS activity. This might be somewhat counterintuitive since people subjectively experience physiological arousal under pressure and naively assume that it mediates performance decrement. In fact, in this study, we found that pressure caused autonomic arousal, but this arousal is not associated with performance decrement. This finding is important because it demonstrates the need to reconsider the traditional arousal theories, which have gained widespread acceptance in the field of social psychology.

There are three possible hypotheses to explain the relationship observed between prefrontal overactivation and performance decrement. The first possibility is derived from the attentional distraction theory (Landers, 1980; Nideffer, 1992): pressure leads to attentional distraction, which reduces the WM capacity and thereby inhibits performance. This hypothesis is consistent with our behavioral data and many earlier findings showing that pressure-induced performance decrement occurred only in tasks with the high WM demands (3-back task in this study) because the performance of such tasks is considered to be easily affected by attentional distraction. Therefore, it is probable that attentional distraction was caused by pressure and manifested as prefrontal overactivation. However, if this hypothesis is correct, pressure should have caused attentional distraction even in the 1-back and 2-back tasks and induced the same level of prefrontal activation as that in the 3-back task, even though it did not cause any detectable behavioral changes; however, no such activation was observed.

The second explanation is derived from the explicit monitoring theory (Beilock & Carr, 2001; Lewis & Linder, 1997; Masters, 1992). This theory proposes that pressure makes people try harder to exert conscious control over the steps they need to carry out. This excessive control is thought to disrupt automated

Table 3. *Correlation Between NIRS and ANS Data for the 3-Back Condition*

	Oxy (ROI 1)	Oxy (ROI 2)	Deoxy (ROI 1)	Deoxy (ROI 2)	Temp	SCL	HR	BVP
NIRS data								
Oxy-Hb in ROI 1	–							
Oxy-Hb in ROI 2	.97**	–						
Deoxy-Hb in ROI 1	−.34	−.39*	–					
Deoxy-Hb in ROI 2	−.65**	−.69**	.70**	–				
ANS data								
Skin temperature	−.04	−.04	.22	.19	–			
SCL	.14	.15	−.57**	−.45*	−.21	–		
Heart rate	.06	.19	−.29	−.22	−.44*	.04	–	
BVP amplitude	−.10	−.11	.50**	.26	.62**	−.39*	−.40*	–

Note. ROI 1 and ROI 2 were placed over the right and left prefrontal cortex, respectively. NIRS = near-infrared spectroscopy, ROI = region of interest, Oxy-Hb = oxygenated hemoglobin, Deoxy-Hb = deoxygenated hemoglobin, ANS = autonomic nervous system, SCL = skin conductance level, BVP = blood volume pulse, Temp = skin temperature, HR = heart rate.
*$p < .05$; **$p < .01$.

processes that normally run outside the scope of WM during performance. Research in cognitive psychology has revealed that recognition judgments in short-term recognition tasks such as the *n*-back task are based on the recollection of details about previous events or on the assessment of stimulus familiarity (Oberauer, 2005; Yonelinas, 2002). Recollection and familiarity are considered to reflect controlled and automatic processes, respectively. If the explicit monitoring hypothesis is accurate, the recollection strategy would become more prominent than the familiarity-based process under pressure. Thus, the prefrontal overactivation observed in the 3-back task might indicate the prominence of recollection. Indeed, neuropsychological and neuroimaging studies have indicated that recollection relies on the prefrontal cortex while familiarity does not (cf. Yonelinas, 2002). However, if pressure does activate the recollection strategy, why did it lead to performance decrement in the 3-back task? A possible explanation is that, since the interval for each trial was comparatively short (2.5 s) in our study, recollection, which requires the renewal of the internal representations of the letter sequence in each trial, was perhaps difficult to achieve in the 3-back task, leading to performance decrement. To verify this possibility, our results should be compared with those obtained from experiments with longer trial intervals.

Third, there is a possibility that prefrontal overactivation did not cause performance decrements; instead, the error recognition in the task brought about a compensatory effort, which manifested as changes in prefrontal activity. In fact, since our results do not prove the direction of the causal relationship between performance decrement and prefrontal activation, this interpretation can be considered probable. However, this hypothesis cannot explain why performance worsened with pressure. Although it can be speculated that a third variable independent of both ANS arousal and prefrontal activation mediates performance decrements, none of the theoretical models advocated to date have proposed such a variable. Therefore, this explanation is not highly probable in isolation. However, it is conceivable that prefrontal overactivation, which can be attributed to attentional distraction or excessive control, causes performance decrements and that this decrement, in turn, arouses additional prefrontal overactivation, creating a vicious circle. This issue requires further investigation through experiments using the event-related design instead of the block design.

The current study has some limitations. First, as mentioned above, we cannot definitively conclude that prefrontal activation mediates pressure-induced performance decrements, since we showed only an association between performance and prefrontal activation. Second, we measured brain activation only in a small portion of the brain, including the frontopolar cortex and a part of dorsolateral prefrontal cortex; the entire lateral frontal cortex was not covered. Moreover, other cortical areas, and, more importantly, subcortical structures, were not covered, because of the general limitations of NIRS. To address these issues, multifaceted and sophisticated research is required.

References

Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of Experimental Psychology: General*, *130*, 701–725.

Bond, F. C., & Titus, L. J. (1983). Social facilitation: A meta analysis of 241 studies. *Psychological Bulletin*, *94*, 265–292.

Carver, C. S., & Scheier, M. F. (1978). Self-focusing effects of dispositional self-consciousness, mirror presence, and audience presence. *Journal of Personality and Social Psychology*, *36*, 324–332.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: L. Erlbaum Associates.

Cottrell, N. B. (1972). Social facilitation. In C. G. McClintock (Ed.), *Experimental social psychology* (pp. 185–236). New York, NY: Holt.

Cui, X., Bray, S., Bryant, D. M., Glover, G. H., & Reiss, A. L. (2011). A quantitative comparison of NIRS and fMRI across multiple cognitive tasks. *NeuroImage*, *54*, 2808–2821.

Drummond, P. D. (1999). Facial flushing during provocation in women. *Psychophysiology*, *36*, 325–332.

Fowles, D. C., Christie, M. J., Edelberg, R., Grings, W. W., Lykken, D. T., & Venables, P. H. (1981). Publication recommendations for electrodermal measurements. *Psychophysiology*, *18*, 232–239.

Geen, R. G., & Gange, J. J. (1977). Drive theory of social facilitation: Twelve years of theory and research. *Psychological Bulletin*, *84*, 1267–1288.

Hirth, C., Obrig, H., Villringer, K., Thiel, A., Bernarding, J., Mühlnickel, W., ... Villringer, A. (1996). Noninvasive functional mapping of the human motor cortex using near-infrared spectroscopy. *NeuroReport*, *7*, 1977–1981.

Hock, C., Müller-Spahn, F., Schuh-Hofer, S., Hofmann, M., Dirnagl, U., & Villringer, A. (1995). Age dependency of changes in cerebral hemoglobin oxygenation during brain activation: A near-infrared spectroscopy study. *Journal of Cerebral Blood Flow and Metabolism*, *15*, 1103–1108.

Hock, C., Villringer, K., MullerSpahn, F., Wenzel, R., Heekeren, H., SchuhHofer, S., & Villringer, A. (1997). Decrease in parietal cerebral hemoglobin oxygenation during performance of a verbal fluency task in patients with Alzheimer's disease monitored by means of near-infrared spectroscopy (NIRS). *Brain Research*, *755*, 293–303.

Hoshi, Y. (2003). Functional near-infrared optical imaging: Utility and limitations in human brain mapping. *Psychophysiology*, *40*, 511–520.

Hoshi, Y. (2005). Functional near-infrared spectroscopy: Potential and limitations in neuroimaging studies. *International Review of Neurobiology*, *66*, 237–266.

Hoshi, Y., & Tamura, M. (1993). Detection of dynamic changes in cerebral oxygenation coupled to neuronal function during mental work in man. *Neuroscience Letters*, *150*, 5–8.

Humphreys, M. S., & Revelle, W. (1984). Personality, motivation and performance: A theory of the relationship between individual differences and information processing. *Psychological Review*, *91*, 153–184.

Huppert, T. J., Hoge, R. D., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2006). A temporal comparison of BOLD, ASL, and NIRS hemodynamic responses to motor stimuli in adult humans. *NeuroImage*, *29*, 368–382.

Jackson, R., & Beilock, S. L. (2008). Attention and performance. In D. Farrow, J. Baker, & C. MacMahon (Eds.), *Developing elite sports performers: Lessons from theory and practice* (pp. 104–118). New York, NY: Routledge.

Jasper, H. (1958). Report of committee on methods of clinical exam in EEG. *Electroencephalography and Clinical Neurophysiology*, *10*, 370–375.

Jennings, J. R., Berg, W. K., Hutcheson, J. S., Obrist, P., Porges, S., & Turpin, G. (1981). Publication guidelines for heart rate studies in man. *Psychophysiology*, *18*, 226–231.

Lancaster, J. L., Woldorff, M. G., Parsons, L. M., Liotti, M., Freitas, C. S., Rainey, L., ... Fox, P. T. (2000). Automated Talairach Atlas labels for functional brain mapping. *Human Brain Mapping*, *10*, 120–131.

Landers, D. M. (1980). The arousal-performance relationship revisited. *Research Quarterly for Exercise and Sport*, *51*, 77–90.

Lewis, B., & Linder, D. (1997). Thinking about choking? Attentional processes and paradoxical performance. *Personality and Social Psychology Bulletin*, *23*, 937–944.

Masters, R. S. W. (1992). Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology*, *83*, 343–358.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167–202.

Miyai, I., Tanabe, H. C., Sase, I., Eda, H., Oda, I., Konishi, I., ... Kubota, K. (2001). Cortical mapping of gait in humans: A near-infrared spectroscopic topography study. *NeuroImage*, *14*, 1186–1192.

Nideffer, R. M. (1992). *Psyched to win*. Champaign, IL: Leisure Press.

Oberauer, K. (2005). Binding and inhibition in working memory: Individual and age differences in short-term recognition. *Journal of Experimental Psychology: General*, *134*, 368–387.

Obrig, H., & Villringer, A. (2003). Beyond the visible: Imaging the human brain with light. *Journal of Cerebral Blood Flow and Metabolism*, *23*, 1–18.

Obrig, H., Wenzel, R., Kohl, M., Horst, S., Wobst, P., Steinbring, J., ... Villringer, A. (2000). Near-infrared spectroscopy: Does it function in functional activation studies of the adult brain? *International Journal of Psychophysiology*, *35*, 125–142.

Okamoto, M., Dan, H., Shimizu, K., Takeo, K., Amita, T., Oda, I., ... & Dan, I. (2004). Multimodal assessment of cortical activation during apple peeling by NIRS and fMRI. *NeuroImage*, *21*, 1275–1288.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.

Schroeter, M. L., Bucheler, M. M., Muller, K., Uludag, K., Obrig, H., Lohmann, G., ... von Cramon, D. Y. (2004). Towards a standard analysis for functional near-infrared imaging. *NeuroImage*, *21*, 283–90.

Schroeter, M. L., Zysset, S., & von Cramon, D. Y. (2004). Shortening intertrial intervals in event-related cognitive studies with near-infrared spectroscopy. *NeuroImage*, *22*, 341–346.

Singh, A. K., Okamoto, M., Dan, H., Jurcak, V., & Dan, I. (2005). Spatial registration of multichannel multi-subject fNIRS data to MNI space without MRI. *NeuroImage*, *27*, 842–851.

Strangman, G., Culver, J. P., Thompson, J. H., & Boas, D. A. (2002). A qualitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activity. *NeuroImage*, *17*, 719–731.

Takahama, S., Ohzawa, I., & Yoshikawa, Y. (2009). Brain activation during processing of emotional valence as measured with near-infrared spectroscopy. *Neuroscience Research*, *65*, S238.

Tanida, M., Katsuyama, M., & Sakatani, . K. (2007). Relation between mental-stress induced prefrontal activity and skin conditions. *Cognitive Brain Research*, *1184*, 210–216.

Tanida, M., Sakatani, K., Takano, R., & Tagai, K. (2004). Relation between asymmetry of prefrontal cortex activities and the autonomic nervous system during a mental arithmetic task. *Neuroscience Letters*, *369*, 69–74.

Tsuzuki, D., Jurcak, V., Singh, A. K., Okamoto, M., Watanabe, E., & Dan, I. (2007). Virtual spatial registration of stand-alone fNIRS data to MNI space. *NeuroImage*, *34*, 1506–1518.

Villringer, A., Planck, J., Hock, C., Schleinkofer, L., & Dirnagl, U. (1993). Near infrared spectroscopy (NIRS): A new tool to study hemodynamic changes during activation of brain function in human adults. *Neuroscience Letters*, *154*, 101–104.

Watanabe, A., & Kato, T. (2004). Cerebrovascular response to cognitive tasks in patients with schizophrenia measured by near-infrared spectroscopy. *Schizophrenia Bulletin*, *30*, 435–444.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language*, *46*, 441–517.

Zajonc, R. B. (1965). Social facilitation. *Science*, *149*, 269–274.

(Received April 2, 2010; Accepted April 11, 2011)