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# Effect of valence, arousal, and modality on cortical activities evoked by emotions

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This study aimed to clarify the association of cortical activity with positive and negative emotions evoked by visual and auditory stimuli. Ten Japanese undergraduate students participated in an experiment where a total of 48 stimuli (24 pictures, 24 sounds) were selected from the International Affective Picture System and the International Affective Digitized Sounds to evoke emotions. These stimuli were grouped according to their valence (positive, negative), arousal (high, low), and modality (vision, audition). Cortical activities from the frontal cortex were recorded using functional near-infrared spectroscopy. The oxygenated hemoglobin (oxy-Hb) signal change was used as the index of cortical activity, and the mean signal change was analyzed by a three-way analysis of variance (valence × arousal × modality). The oxy-Hb related to negative emotion was significantly larger in the right frontal area. The specific relationship between arousal level and cortical activity was undetected. The oxy-Hb levels in the visual and auditory conditions declined. This study suggests that negative emotions evoked by distant sensations are related to the right dorsolateral prefrontal cortices, and the arousal level affected by stimuli and the sensory modality of stimuli have no effect on a variety of the regions of cortices activated by emotion; each region responds equally to several stimuli that vary with arousal level and modality. However, there were some limitations to this study.

**Keywords:** emotion, cortices, modality, functional near-infrared spectroscopy

## Effect of valence, arousal, and modality on cortical activities evoked by emotions

In our daily lives, we receive numerous pieces of information about the external world and internal environment via our sensory systems. These systems are called the five senses: visual, auditory, olfactory, taste, and touch. Information obtained by the systems is processed and interpreted in the brain. However, the five senses not only obtain information and convey it to the brain, they are also related to evoking emotions. Furthermore, they work simultaneously and interact with each other. On the beach during a summer vacation, for instance, the beautiful view (visual) and the sound of the waves (auditory) make us feel invigorated. In addition, if salty ocean air (olfactory) and hot sand (touch) are also recognized, it will make us more excited. In fact, adding stimuli that are recognized by the sensory system intensifies emotional experiences (e.g., Rainer et al., 2012).

Technologies that provide emotional experiences such as virtual reality (VR) and four-dimensional (4D) films are rapidly developing. It is expected that clarifying which sensory

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modality is influential in emotional evocation contributes to the progression of these technologies. In particular, technologies for communicating with people who live in remote places, such as Google Meet (Google Inc., Calif., US) and Zoom (Zoom Video Communications Inc., Calif., US), have received much attention due to the influence of the COVID-19 pandemic. The information provided by these communicational technologies is mainly recognized by vision and audition. Thus, vision and audition are the focus of this study.

Emotion is described in two-dimensional coordinates. One axis is pleasure–displeasure, while the other is the degree of arousal (Russell, 1980) (Figure 1). Emotive states such as excitement, delight, and happiness are classified in the pleasure–high arousal quadrant. Emotive states such as pleasure, satisfaction, and relaxation are classified in the pleasure–low arousal quadrant. Emotive states such as frustration, fear, and anger are classified in the displeasure–high arousal quadrant. Emotive states such as sadness, boredom, and listlessness are classified in the pleasure–low arousal quadrant (Russell, 1980). Some earlier studies reported that the left side of the prefrontal cortex responded to positive emotions, whereas the right side of the prefrontal cortex responded to negative emotions (e.g., Okamoto, 2005; Plichta et al., 2011). Although another study reported that both sides of the dorsolateral prefrontal cortices were activated by negative emotions (Aldhafeeri, Mackenzie, Kay, Alghamdi, & Sluming, 2012), yet another study reported that both sides of the dorsolateral prefrontal cortices were activated by positive emotions (Yamamoto, Tsunashima, & Yanagisawa, 2013). Although the relationship between emotions and brain activity has been examined in a number of studies, it is still unclear. In addition, there is a possibility that the results of preceding studies are limited because only the visual or auditory stimuli were used to evoke emotions. Therefore, this study aimed to clarify the association of cortical activities with positive and negative emotions evoked by distant sensations, namely, vision and audition.

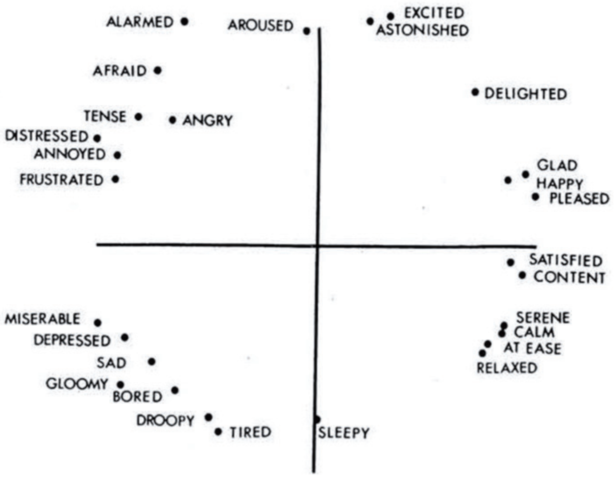

*Figure 1.* Russell's Multidimensional Scaling of Terms (Russell, 1980).

Furthermore, functional near-infrared spectroscopy (fNIRS) was adopted as a brain imaging technique in this study. Using fNIRS to measure brain activity has some advantages over other brain imaging techniques, such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI). First, fNIRS is highly non-invasive and can be used without the direction of doctors because it uses only near-infrared light with no radioactive agents or strong magnetics to measure brain activity. This means that anyone who knows how to use the fNIRS system can handle it. Further, measurement without something invasive enables repeated use on the same participants within short intervals. Second, fNIRS allows participants to have an unrestricted posture during measurement. This enables the measurement of brain activity not only without limiting participants' posture, but also in conditions that are close to our daily lives. Therefore, we adopted fNIRS to measure cortical activity in this study.

## Methods

### *Participants*

A total of 10 undergraduate students from Iwate University (four men, six women; $M_{age}$ = 21.4 years, *SD* = 0.70) participated in this experiment. The participants were recruited on the website of Iwate University. All participants had normal 20/20 vision in both eyes with or without correction, and they did not wear a hearing aid in their daily lives. All participants provided written informed consent. This experiment was designed based on the Declaration of Helsinki for Research Involving Human Subjects and was approved by the committee of Medical and Health Research Involving Human Subjects at Iwate University and Tohoku University.

### *fNIRS System*

LABNIRS FOILE-3000 (Shimadzu Corp., Kyoto, Japan) was used to measure hemodynamic brain responses from the frontal area of the participants' brains. This system consists of 12 emitters and 12 detector probes, which consist of 37 channels (Ch), and monitors reflected lights every 39 ms. The head-holder was used to set the probes, which were placed 3 × 8 over the frontal cortex, 3 cm apart from each other. The probes were placed with reference to the International 10-20 system, and Ch 34 was located at Fpz (Figure 2). To prevent body movements and artifacts, participants' heads were placed on a chin rest during the recording. While the relative concentration changes in oxygenated hemoglobin (oxy-Hb), deoxygenated hemoglobin (deoxy-Hb), and total hemoglobin were recorded, the oxy-Hb signal change was used as the index of brain activity because it is more sensitive to hemodynamic response than deoxy-Hb and total hemoglobin (Hoshi, 2003; Strangman, Culver, Thompson, & Boas, 2002).

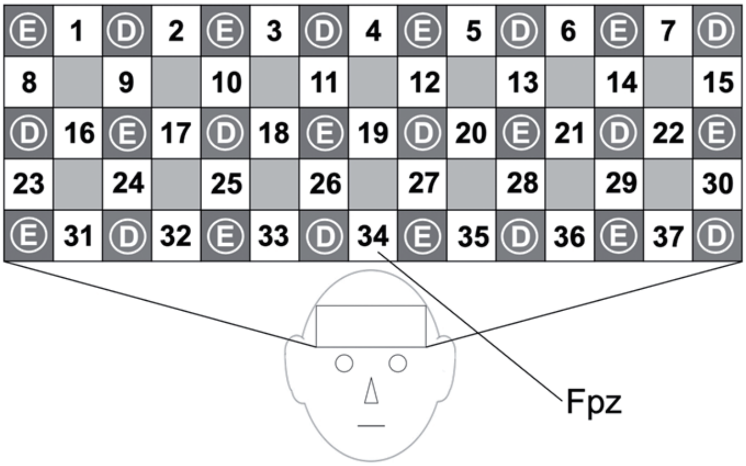

*Figure 2*. The schematic illustration of the placement of the fNIRS. "E" is emitter. "D" is detector. The numbers are channels. The channel 34 was located at Fpz.

### *Stimuli*

Visual stimuli, the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1997), was used to evoke positive and negative emotions. A total of 24 pictures (6 positive, high arousal: $M_{\text{valence}} = 6.94$, $M_{\text{arousal}} = 5.73$; 6 positive, low arousal: $M_{\text{valence}} = 7.43$, $M_{\text{arousal}} = 3.02$; 6 negative, high arousal: $M_{\text{valence}} = 2.19$, $M_{\text{arousal}} = 6.25$; 6 negative, low arousal: $M_{\text{valence}} = 3.04$, $M_{\text{arousal}} = 4.81$) were selected. Pictures were presented on a 23.8-inch ASUS VZ239HR monitor (ASUSTek Computer Inc., Taipei, Taiwan) with a pixel resolution of 1,920 × 1,080. The viewing distance was 57 cm. The dimensions of the pictures were 25° width × 20° height. The background color of the monitor was gray (red: 128; green: 128; blue: 128) for the task. Auditory stimuli, the International Affective Digitized Sounds 2nd Edition (IADS-2; Lang & Bradley, 2007), were used to evoke positive and negative emotions. A total of 24 sounds (6 positive, high arousal: $M_{\text{valence}} = 5.87$, $M_{\text{arousal}} = 6.73$; 6 positive, low arousal: $M_{\text{valence}} = 6.50$, $M_{\text{arousal}} = 4.92$; 6 negative, high arousal: $M_{\text{valence}} = 2.32$, $M_{\text{arousal}} = 6.88$; 6 negative, low arousal: $M_{\text{valence}} = 3.58$, $M_{\text{arousal}} = 4.47$) were selected. The sounds were presented to participants via AirPods (Apple Inc., Cupertino, US). The volume of the sounds was approximately 65 db. The task consisted of four 372-s series (372 s × 4). The series was composed of four 78-s blocks (78 s × 4) as positive–high arousal, positive–low arousal, negative–high arousal, and negative–low arousal conditions. Two of the four series had two blocks that presented pictures and two blocks that presented sounds. The other two series had four blocks that randomly presented pictures and sounds. At the beginning of each block, a fixation point was presented at the center of the monitor for 60 s. Three stimuli that conformed to the conditions were presented for 6 s each (Figure 3). The order of the four series, the order of the four blocks, and the order of pictures and sounds were randomized. Each

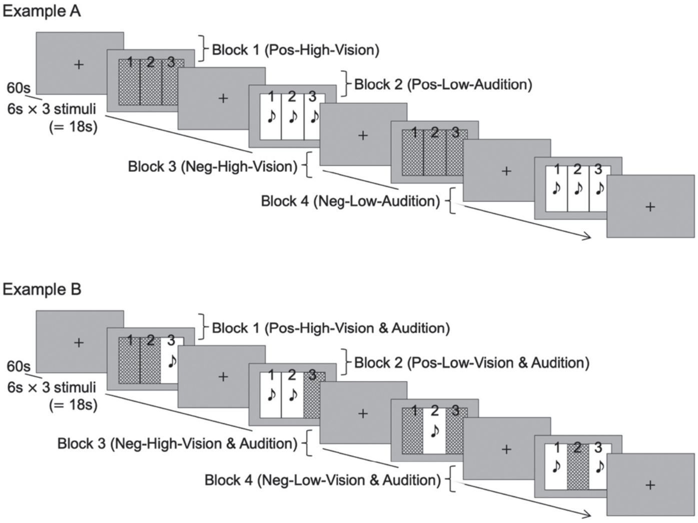

*Figure 3*. The design of how to present the stimuli. The upper is the example of the series which had two blocks on which pictures are presented and two blocks on which sounds are presented (Example A). The lower is the example of the series which had four blocks on which pictures and sounds are presented randomly (Example B).

picture and sound were presented only once. For the presentation of stimuli, Psychophysics Toolbox ver. 3.0.12 (http://psychtoolbox.org) and MATLAB R2016b (MathWorks. Mass, US) on a MacBook Air (13-inch Mid 2012, OSX 10.9.5 Mavericks) (Apple Inc., Cupertino, US) were used.

### *Procedure*

The experiment was conducted in a quiet room with a constant temperature of 23-25℃. Black boards surrounded the monitor as a countermeasure against the effect of the environment.

Participants were provided with explanations and instructions regarding the experiment. They were told that the experiment aimed to reveal the relationship between emotion and sensory systems. All participants provided written approval for participation. For the experiment, participants sat approximately 57 cm away from the monitor, fitted with fNIRS probes on their head. The light in the room was turned off, and the participants gazed at the monitor, after which the task began.

At the end of the task, the fNIRS probes were removed from participants' heads. Thereafter, all pictures and sounds were presented one by one, and the participants were instructed to evaluate the valence and arousal of each picture and sound with the Self-Assessment Manikin (SAM; Bradley & Lang, 1994). The Self-Assessment Manikin used in this study was quoted from Lang et al. (2008) (Figure 4). The participants were asked to select the

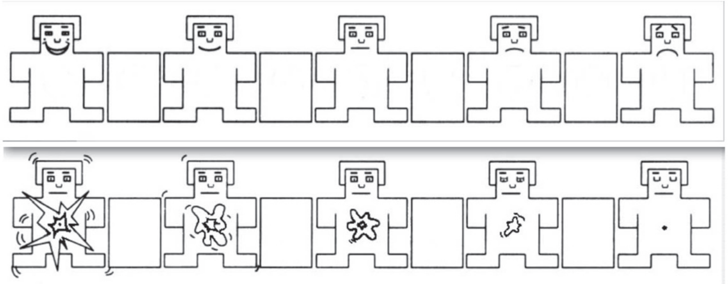

*Figure 4.* The Self-Assessment Manikin (Lang et al., 2008). The upper is the scale for evaluating the valence of stimuli. The lower is the scale for evaluating the arousal of stimuli.

left side of the figure in the upper scale when they felt completely happy, pleased, satisfied, and hopeful in relation to the presented stimuli. Participants were asked to select the right side of the figure in the upper scale when they felt completely unhappy, annoyed, unsatisfied, and despaired in relation to the presented stimuli. The participants were asked to select the left side of the figure in the lower scale when they were extremely excited, activated, felt awake, and aroused in relation to the presented stimuli. Participants were asked to select the right side of the figure in the lower scale when they were extremely calm, relaxed, felt sleepy, and unaroused in relation to the presented stimuli.

### *Data Analysis*

Data from two subjects were excluded from the analysis due to procedural reasons. For each participant, the recorded waveforms of the oxy-Hb signal were smoothed by a high-pass filter (filter degree was 500, cutoff frequency was 0.01 Hz) and low-pass filter (filter degree was 500, cutoff frequency was 0.3 Hz). After that, the waveforms were corrected to the baseline, and standardized with the SD of oxy-Hb in the range of 5 s before the onset of stimuli. The processes were conducted using MATLAB R2019b with reference to Ono's method (2018). The average of oxy-Hb 10-30 s after onset of the stimuli was regarded as a change of oxy-Hb. Subsequently, a three-way (valence, arousal, and modality) analysis of variance (ANOVA) was used for each channel. The valence and arousal factors both had two levels (positive and negative, and high and low, respectively). The modality factor had three levels (picture, sound, picture, and sound). Statistical analysis was conducted using R ver. 3.6.2 (https://www.r-project.org/).

## Results

### *Evaluation of Stimuli*

To examine whether the visual and auditory stimuli were appropriately divided into positive and negative conditions with valence axes, a two-way ANOVA (valence × modality) was conducted. The mean scores of the valence of visual stimuli in positive and negative conditions were 6.90 (*SE* = 0.47) and 1.98 (*SE* = 0.41), respectively. The mean scores of the valence of auditory stimuli on positive and negative conditions were 6.47 (*SE* = 0.47) and 2.17 (*SE* = 0.33), respectively. A two-way ANOVA revealed the effect of valence; the mean score of the valence of positive stimuli was higher than that of negative stimuli ($F$ (1, 7) = 256.9, $p < .01$) (Figure 5). Further, to examine whether the visual and auditory stimuli were appropriately divided into high and low conditions with arousal axes, a two-way ANOVA was conducted. The mean scores for the arousals of visual stimuli on high and low conditions were 5.74 (*SE* = 0.73) and 2.84 (*SE* = 0.51), respectively. The mean scores for the arousals of auditory stimuli on high and low conditions were 6.31 (*SE* = 0.58) and 4.08 (*SE* = 0.59), respectively. A two-way ANOVA (arousal × modality) revealed a significant interaction between arousal and modality ($F$ (1, 7) = 11.13, $p < .05$), the effect of arousal ($F$ (1, 7) = 208.5, $p < .01$), and the effect of modality ($F$ (1, 7) = 25.83, $p < .01$). Post hoc analysis (Bonferroni's method) of the interaction revealed that the mean score of the arousal of auditory stimuli was

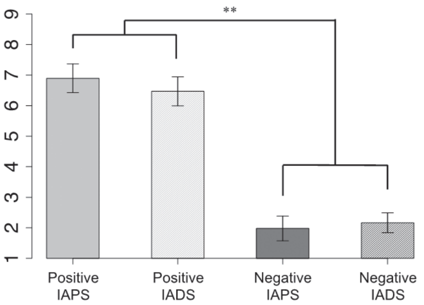

*Figure 5*. The horizontal axis indicates the positive and the negative conditions on visual stimuli and auditory stimuli. The vertical axis is evaluated valence values by participants. The error bars represent standard error of the mean. (**: $p < .01$)

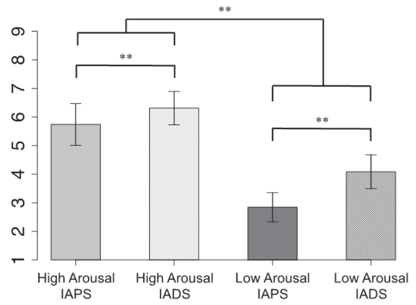

*Figure 6*. The horizontal axis indicates the high arousal and the low arousal conditions on visual stimuli and auditory stimuli. The vertical axis is evaluated arousal values by participants. The error bars represent standard error of the mean. (**: $p < .01$)

higher than that of visual stimuli ($p < .01$) (Figure 6).

### *fNIRS Data*

For each participant, the obtained waveforms of the oxy-Hb signal changes were normalized. The mean signal changes during the analysis period were then calculated (Figure 7). To examine the effect of valence, arousal, and the modality of stimuli on brain activity, the mean signal change was analyzed by a three-way ANOVA for each channel. On the valence of stimuli, ANOVA revealed a significant interaction between valence and modality in parts of the right frontal area (Ch 3, $F$ (2, 14) = 5.25, $p < .05$; Ch 9, $F$ (2, 14) = 6.57, $p < .01$). Post hoc analysis of the interaction revealed that the change in oxy-Hb in the negative–picture condition was larger than that in the positive–picture condition (Ch 3, $t$ (7) = 2.85, $p < .05$; Ch 9, $t$ (7) = 3.55, $p < .01$) (Figure 8). On the arousal of stimuli, ANOVA revealed a significant interaction between arousal and modality on Ch 37 ($F$ (2, 14) = 6.51, $p < .05$). Post hoc analysis of the interaction revealed that the change in oxy-Hb in the high–picture condition was larger than that of in the low–picture condition ($t$ (7) = 3.92, $p < .01$). Further, ANOVA also revealed the effect of arousal on two channels (Ch 13, $F$ (1, 7) = 8.11, $p < .05$; Ch 20, $F$ (1, 7) = 6.58, $p < .05$); the change in oxy-Hb in the low condition was seen to be larger than that in the high condition on Ch 13 and Ch 20 (Figure 9). Regarding the modality of stimuli, ANOVA revealed a significant interaction between arousal and modality on Ch 24 ($F$ (2, 14) = 5.39, $p < .01$). Post hoc analysis of the interaction (Bonferroni's method) revealed that the change in oxy-Hb in the high–picture condition was larger than that in the high–picture and sound condition ($t$ (14) = 3.59, $p < .01$). ANOVA also revealed the tendency of interaction between arousal and modality ($F$ (2, 14) = 2.91, $p = .09$) and the significant effect of arousal ($F$ (1, 7) = 7.21, $p < .05$) and modality ($F$ (2, 14) = 5.29, $p < .05$) on Ch 17. Post hoc analysis of the interaction (Bonferroni's method) revealed that the change in oxy-Hb in the high–picture condition was larger than that in the high–picture and sound condition ($t$ (14) = 3.07, $p < .05$). Further, ANOVA revealed the effect of modality on some channels (Ch 1, $F$ (2, 14) = 7.65, $p < .01$; Ch 16, $F$ (2, 14) = 10.12, $p < .01$; Ch 26, $F$ (2, 14) = 3.74, $p < .05$; Ch 34, $F$ (2, 14) = 4.02, $p < .05$). Post hoc analysis of the effect of modality (Bonferroni's method) revealed that the changes in oxy-Hb in the picture and sound conditions were seen to be larger than that in the picture and sound conditions on Ch 1 ($t$ (14) = 2.99, $p < .05$; $t$ (14) = 3.38, $p < .05$). This post hoc analysis also revealed that the change in oxy-Hb in the picture condition was larger than that in the picture and sound condition (Ch 16, $t$ (14) = 4.35, $p < .01$; Ch 26, $t$ (14) = 2.74, $p < .05$; Ch34, $t$ (14) = 2.64, $p = .06$) (Figure 10).

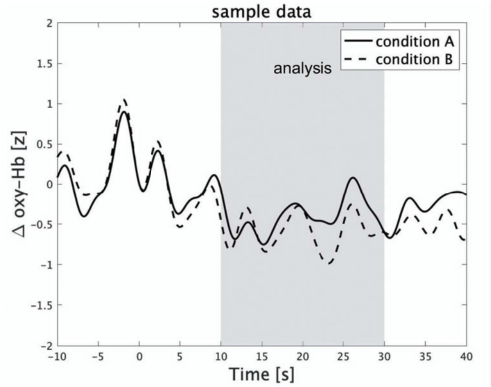

*Figure 7*. Representative example of average of oxy-Hb signal change waveforms. The mean signal change during 10-30 s after the onset of the stimuli was calculated and used as the index of brain activity.

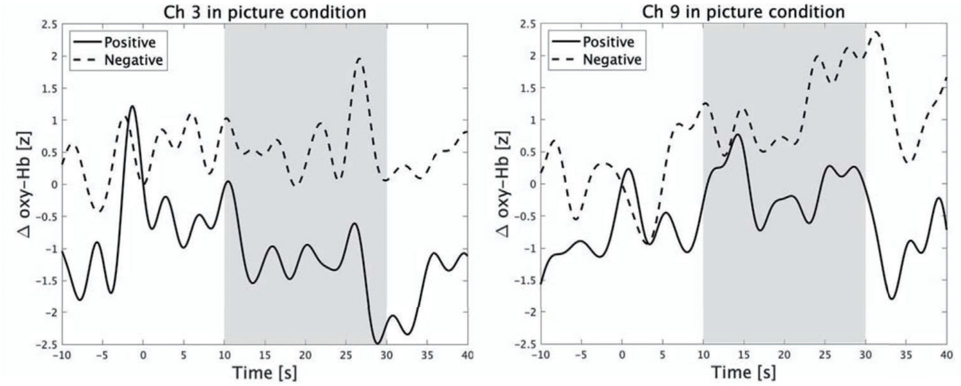

*Figure 8*. The average of oxy-Hb signal change waveforms on Ch 3 (left) and Ch 9 (right). The solid line is the waveforms of oxy-Hb in positive condition. The dashed line is the waveforms of oxy-Hb in negative condition.

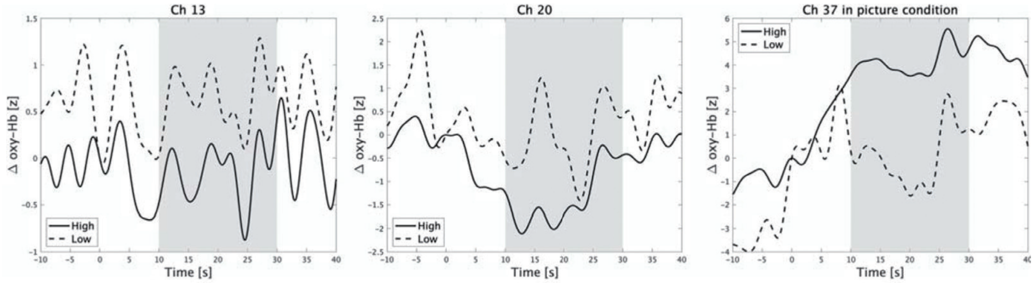

*Figure 9*. The average of oxy-Hb signal change waveforms on Ch 13 (left), Ch 20 (center), and Ch 37 (right). The solid line is the waveforms of oxy-Hb in high arousal condition. The dashed line is the waveforms of oxy-Hb in low arousal condition.

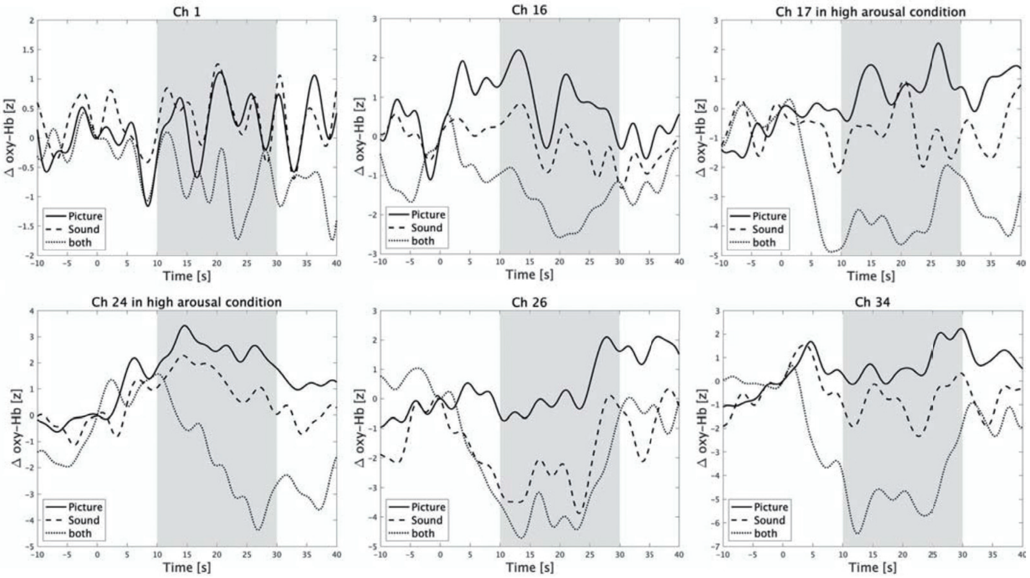

*Figure 10.* The average of oxy-Hb signal change waveforms on Ch 1 (upper left), Ch 16 (upper center), Ch 17 (upper right), Ch 24 (lower left), Ch 26 (lower center), and Ch 34 (lower right). The solid line is the waveforms of oxy-Hb in picture condition. The dashed line is the waveforms of oxy-Hb in sound condition. The dotted line is the waveforms of oxy-Hb in picture and sound condition.

## Discussion

This study aimed to clarify the association of cortical activity with positive and negative emotions evoked by visual and auditory stimuli. The results of the subjective evaluation indicated that both the visual and auditory stimuli were correctly divided into four types based on their valence and arousal properties. The fNIRS data showed that negative emotions were related to the right hemisphere. Further, it was suggested that the arousal level affected by the stimuli and the sensory modality of stimuli have no effect on a variety of the regions of cortices activated by emotion.

The visual stimuli, IAPS, and the auditory stimuli, IADS, were evaluated based on their valence and arousal properties by all participants in this experiment. Regarding the valence properties, the visual stimuli were divided into positive and negative pictures. Similarly, auditory stimuli were divided into positive and negative sounds. Regarding the arousal properties, both positive and negative pictures were divided into high and low arousal pictures. Similarly, both positive and negative sounds were divided into high and low arousal sounds. These results suggest that the visual and auditory stimuli in this experiment were appropriately divided based on their valence and arousal properties, and were adequate to evoke emotions. Although the evaluated arousal level of auditory stimuli was higher than that of visual stimuli, it was a natural result because the arousal level of auditory stimuli used in this study tended to be higher than that of visual stimuli.

Regarding the valence of stimuli, the fNIRS data showed that the oxy-Hb was significantly larger in some parts of the right hemisphere in the negative condition. This area corresponds to part of the dorsolateral prefrontal cortices. Some earlier studies reported that the activity of the right dorsolateral prefrontal cortex with negative emotions were evoked by visual or auditory stimuli (e. g., Okamoto, 2005; Plichta et al., 2011). Furthermore, an earlier study reported the activity of both sides of the dorsolateral prefrontal cortex with negative emotions evoked by visual stimuli (Faten et al., 2012). Based on these results, it is suggested that negative emotions evoked by distant sensations are related to the right hemisphere, especially the right dorsolateral prefrontal cortices. However, other studies reported the relationship between positive emotions evoked by visual or auditory stimuli and the right hemisphere (e.g., Asano, Hiroshige, & Ide, 2011; Yamamoto, Yanagisawa, & Tsunashima, 2012). There is a possibility that emotions evoked by distant sensations are related to both hemispheres rather than to only one side, and further research is needed to clarify the region of the brain activated by emotions.

Regarding the arousal of stimuli, the fNIRS data showed that the oxy-Hb in the high arousal condition was low compared to that in the low condition on two channels. In contrast, the oxy-Hb in the high condition was larger than that in the low arousal condition on one channel. A specific relation between the arousal level and the position of the channels was not detected. It was suggested that the arousal level affected by the stimuli does not have a relationship with a specific region of the cortices. Although it was expected that the high arousal stimuli activated the brain more strongly than the low arousal stimuli, the results in this study did not support this hypothesis. It is supposed that the arousal level of participants was uncorrelated with the arousal of stimuli. In this study, it was unclear whether the high arousal stimuli induced higher arousal levels in participants because the evaluation of stimuli was conducted independently to measure brain activity. It is necessary to compare the physiological and behavioral data in further research.

Regarding the modality of stimuli, fNIRS data showed that the oxy-Hb in the visual and auditory conditions was decreased compared to both the visual and the auditory condition. There is the possibility that this result was caused by the shift of attention; participants needed to shift the focus of their attention to stimuli because the visual and the auditory stimuli were presented individually in this study. Although further research will clarify the difference between vision and audition for evoking emotions, it is suggested that the sensory modality of stimuli caused no differences in the region of cortices activated by emotion.

## Limitations and Recommendations for Future Research

This study has some limitations. First, the sample size was small. Ten participants participated in this study, and eight participants' data were analyzed. The number of samples would not be sufficient to reflect relevant results because some preceding studies that measured the activity of the brain with fNIRS obtained more than 20 participants' data (e.g., Sasaki & Sakai, 2020; Watanabe et al., 2011). Therefore, future research requires more participants; the results may be different if the number of available samples for analysis exceeded 20.

Second, the baseline correction of oxy-Hb waveforms is insufficient. Although all oxy-Hb values at 0 s were 0, some waveforms showed much higher (or much lower) values than 0 before the stimuli were presented. This issue is likely to have induced incorrect results. For instance, comparing two waveforms with the same values would show that one is higher than the other if one has a higher baseline, despite there being no actual differences between the two waveforms. There is a possibility that the data processing in this study is mismatched for the obtained oxy-Hb waveforms. Therefore, it is necessary to examine the obtained raw data in detail and apply the appropriate processing methods for the properties of the data in future research.

Third, the reason why some oxy-Hb waveforms showed negative values is still unclear. It has been suggested that the decline of oxy-Hb in the frontal region during passive musical listening reflects a relaxed state by suppressing brain activity (Iwasaka et al., 2007). Furthermore, the relationship between the decline of oxy-Hb in the prefrontal cortex and a sense of immersion in listening to music has been reported (Suda, Mori, Yamaoka, Hattahara, & Katayose, 2006). However, it was reported that during the playing of the electronic organ, oxy-Hb concentration on the right side of the prefrontal cortex was negatively correlated with that in the right auditory cortex (Iwasaka et al., 2007). Moreover, it was suggested that the decline of oxy-Hb in the center of the frontal area during the observation of emotional stimuli was caused by the outflow of blood into other activated regions such as the amygdala (Asano et al., 2011; Yamamoto et al., 2013). It is possible that the decline of oxy-Hb is caused by evoking feelings of relaxation and/or by activities in some areas close to the prefrontal cortex. Therefore, consideration of the correlation between behavioral data and fNIRS data is required in future research. Furthermore, the comparison between channels for fNIRS data and/or the measurement of areas other than the prefrontal cortex are also required in future research.

## Conclusion

This study concludes that negative emotions evoked by distant sensations are related to the right hemisphere, especially the right dorsolateral prefrontal cortices. Further, this study concludes that the arousal level affected by the stimuli and the sensory modality of stimuli have no effect on a variety of the regions of cortices activated by emotion; each region responds equally to several stimuli that vary with arousal level and modality. However, this study has some limitations. Further research is needed to improve the limitations, and to clarify in greater detail the association of cortical activities with positive and negative emotions evoked by distant sensations.

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