Enhancement of Activity of the Primary Visual Cortex During Processing of Emotional Stimuli as Measured With Event-Related Functional Near-Infrared Spectroscopy and Event-Related Potentials

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Abstract: In this study we investigated whether event-related near-infrared spectroscopy (NIRS) is suitable to measure changes in brain activation of the occipital cortex modulated by the emotional content of the visual stimuli. As we found in a previous pilot study that only positive but not negative stimuli differ from neutral stimuli (with respect to oxygenated haemoglobin), we now measured the event-related EEG potentials and NIRS simultaneously during the same session. Thereby, we could evaluate whether the subjects ($n = 16$) processed the positive as well as the negative emotional stimuli in a similar way. During the task, the subjects passively viewed positive, negative, and neutral emotional pictures (40 presentations were shown in each category, and pictures were taken from the International Affective Picture System, IAPS). The stimuli were presented for 3 s in a randomized order (with a mean of 3 s interstimulus interval). During the task, we measured the event-related EEG potentials over the electrode positions O1, Oz, O2, and Pz and the changes of oxygenated and deoxygenated haemoglobin by multichannel NIRS over the occipital cortex. The EEG results clearly show an increased early posterior negativity over the occipital cortex for both positive as well as negative stimuli compared to neutral. The results for the NIRS measurement were less clear. Although positive as well as negative stimuli lead to significantly higher decrease in deoxygenated haemoglobin than neutral stimuli, this was not found for the oxygenated haemoglobin. *Hum Brain Mapp* 29:28–35, 2008. © 2007 Wiley-Liss, Inc.

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INTRODUCTION

The functional neuroanatomy of emotion has been widely examined e.g. using the blood oxygen level-dependent functional magnetic resonance imaging [Davis and Whalen, 2001; Pessoa et al., 2002; Phan et al., 2002]. This research approach revealed that the processing of emotional in comparison to neutral visual stimuli leads to an increased activation of various cortical areas, including the amygdala, the medial prefrontal cortex, and, interestingly, also sensory areas such as the visual cortex

[Junghöfer et al., 2001; Phan et al., 2002]. Moreover, it was shown that emotional arousal modulates the amplitudes of the event-related potentials (ERPs) at two time windows. As early as 240 ms after the stimulus presentation, an early posterior negativity (EPN) for emotional compared to neutral visual stimuli was localized over the occipital cortex [Schupp et al., 2003]. It was argued that this EPN reflects facilitated sensory encoding of affective stimuli by naturally occurring selective attention. Additionally, a second effect starts approximately 300 ms after the stimulus presentation over the parietal cortex, with more positive amplitudes to emotional in comparison to neutral stimuli (slow wave, SW) [Cuthbert et al., 2000; Schupp et al., 2000]. This effect is considered to index postsensory (higher-order) stages of stimulus evaluation. Altogether there is evidence that emotional stimuli, positive as well as negative, lead to an increased activation of the occipital cortex.

This activation can be theoretically explained by the evolutionary need to quickly detect potentially meaningful stimuli [Ohman and Mineka, 2001]. The amygdala that is central to emotional processing has been speculated to prime and modulate primary visual circuits [Davis and Whalen, 2001; LeDoux, 1998]. Indeed, feedback loops from brain regions such as the amygdala [Amaral et al., 1992] or the anterior cingulate [Posner and Raichle, 1995] to visual areas have been documented. We have previously shown that this can boost the dominance of emotional pictures over neutral pictures [Alpers and Pauli, 2006; Alpers et al., 2005b].

A possible explanation may be natural selective attention [Lang, 1997]. Individuals are more likely to attend to stimuli of evolutionary importance than to others and situations with an emotional content outrank neutral situations. Natural selective attention led to a stronger activation of the occipital cortex while viewing emotional pictures than neutral pictures [Lang et al., 1998]. Furthermore, the emotional content of pictures seems to enhance not only brain activity but also the recognition of emotional pictures [Abrisqueta-Gomez et al., 2002; Dolcos and Cabeza, 2002].

Recently near-infrared spectroscopy (NIRS), a method using light of the infrared spectrum, has been introduced to investigate changes of cerebral oxygenation. NIRS is based on the facts that (1) light of the near infrared spectrum can penetrate biological tissue and (2) the changes in the absorbed near infrared light over a task can be ascribed to changes in oxygenated and deoxygenated haemoglobin concentrations (for a more detailed description of the methods see [Hoshi, 2003; Obrig and Villringer, 2003]. The correspondence between neural activity and changes in oxygenation can be described as follows: Regional brain activation leads to an increasing metabolism, which is followed by an increased regional cerebral blood flow (rCBF). It has been well documented that the increased rCBF exceeds the oxygenation demand of the tissue, which leads to increased $[O_2Hb]$ and to decreased $[HHb]$ as a sign of activation [Fox and Raichle, 1986]. The

changes in $[O_2Hb]$ are typically more prominent than those in $[HHb]$, with higher changes in amplitudes as well as larger involved brain areas. It was argued that changes in $[O_2Hb]$ are under a stronger influence of arterial compartments in contrast to $[HHb]$, which comes mostly from the venous compartments [Franceschini et al., 2003]. Therefore, $[O_2Hb]$ might be more under the influence of systemic contributions like heart rate and thus represent a less localized activation than $[HHb]$ maps. In recent years, NIRS has been used to measure changes in brain oxygenation due to cognitive tasks [Herrmann et al., 2005; Horowitz and Gore, 2004; Schroeter et al., 2002; Strangman et al., 2002] but to a lesser extent during emotional tasks [Herrmann et al., 2003].

The aim of this study was to evaluate whether NIRS is suitable to measure changes in brain activation of the occipital cortex modulated by the emotional content of the visual stimuli. In a first pilot study [Alpers et al., 2005a] we used a block design with positive, negative, and neutral pictures from the International Affective Picture System (IAPS) [Lang et al., 1999], which were passively viewed by the individuals. In this study, we found increased brain activation over the occipital cortex to the visual stimuli but the emotional modulation was less clear. The effects were rather small and significantly only for higher $[O_2Hb]$ for the positive but not for the negative stimuli in comparison to neutral stimuli. In the current study we used the same IAPS pictures but presented them in a randomized order to exclude any effects caused by expectancies of the subjects. To include a second parameter for emotional processing, we additionally measured the event-related EEG potentials to the stimuli parallel to the NIRS measurement. The signals of NIRS and EEG do not influence each other and therefore a combination is possible [Ehlis et al., submitted; Horowitz and Gore, 2004]. Here we measured both the EEG and NIRS over the same brain areas (the occipital cortex) with the EEG electrodes always placed in between a light emitter and a light detector.

METHODS

Participants

Sixteen healthy volunteers (11 women), age ranging from 21 to 30 years (mean age 24.2 ± 2.4 years), participated after written informed consent was obtained. All participants had corrected-to-normal vision and all except one were right handed. None of them took psychoactive medication.

Stimulus Material

One hundred and twenty pictures were selected on the basis of their normative valence and arousal from the IAPS, a collection of standardized photographic material [Lang et al., 1999]. Forty of these are positive and in high arousal, 40 negative and in high arousal, and 40 neutral

and in low arousal. Each picture was shown for 3 s on a black screen located 100 cm in front of the subject in a shaded room. Additionally, there were 40 null events showing a black screen for 3 s. A variable interstimulus interval (ISI) of 2–4 s appeared between the pictures. The task of the participants was to simply view the sequentially presented images; no response was required. The sequence of the pictures and the null events was randomized. ERP and NIRS data were recorded for a total of 160 trials lasting 30 min.

EEG Recording

The EEG was recorded from four scalp electrodes positioned according to the international 10–20 system at the positions O1, O2, Oz, and Pz. An electrode between Fpz and Fz was connected to the ground, and a further electrode at the root of the nose was used as the recording reference. Three additional channels recorded the electrooculogram from the outer canthi of both eyes and below the right eye to monitor eye blinks. The EEG was sampled continuously at a rate of 1000 Hz with a bandpass from 0.1 to 70 Hz. Impedances were kept at 5 k Ω or below. Epochs (–200 ms before stimulus onset to 800 ms) with amplitudes or with a voltage step exceeding ± 100 μ V were excluded from further analyses. The artifact-free trials (at least 20 epochs) were averaged separately for each subject and condition. Data were filtered offline with a bandpass from 1 to 15 Hz. A baseline correction with the baseline between –200 ms and stimulus onset was calculated.

For the EPN we calculated the mean amplitudes in the time window between 250 and 350 ms for all three conditions. The SW was determined by peak detection between 420 and 600 ms for every single subject and condition. The EEG-data of one participant could not be analyzed due to data loss. EEG data were analyzed using ANOVAs for repeated measures with the within-subjects factors electrode (O1/O2/Oz/Pz) and condition (positive/negative/neutral) using SPSS 13.0.

NIRS Recording

NIRS-measurement was performed with a continuous wave system (ETG-4000, Hitachi Medical, Japan) with a 3 $\times$ 5 optode probe set (consisting of 7 photodetectors and 8 light emitters, resulting in a total of 22 channels). The probe set was placed on the occipital cortex with channel 15 placed above electrode O1, channel 16 placed above electrode Oz, and channel 17 placed above electrode O2 (Fig. 3). Two different wavelengths (695 ± 20 nm and 830 ± 20 nm) are used by the system, and its frequency is modulated for wavelengths and channels to prevent crosstalk. Reflected light (not absorbed) leaving the tissue is received by the photodetectors and transmitted into a set of lock-in amplifiers that are limited to the particular frequencies of interest. Both wavelengths are used to solve the modified Beer-

Lambert equation for highly scattering tissue that allows estimating changes in [HHb] and [O₂Hb] based on the measurements. Since continuous wave systems cannot measure the optical path length [Hoshi, 2003] the scale unit is the molar concentration multiplied by the unknown path length (mmol $\times$ mm). The interoptode distance was 30 mm, which results in measuring approximately 15 mm [Okada and Delpy, 2003] to 25 mm [Hoshi et al., 2006] beneath the scalp. Although the exact extent of the brain region examined by each set of NIRS probes cannot be determined, the region examined is thought to be a banana-shaped region between the two optodes, with a depth of 0.9–1.3 cm from the brain surface [Koizumi et al., 1999; Villringer et al., 1997]. Sampling rate was set to 10 Hz.

NIRS Data Analysis

The data were analyzed as described before [Plichta et al., 2006]. To remove baseline drifts and pulsation due to heartbeat, the raw data were preprocessed by a high-pass filter of 0.02 Hz. The preprocessed data were then analyzed by the two-stage ordinary least squares (OLS) estimation methodology according to the general linear model. A Gauss function was used for the haemodynamic response function (HRF). At the single subject level, we included the first and second temporal derivative of HRF in order to modulate the onset as well as the dispersion of the HRF. A δ function indicating the onset of sensory stimulation was convolved with the predictors for each condition. Thereafter, the first-stage OLS estimation was performed. We corrected our analyses for serial, correlated errors by fitting a first-order autoregressive process to the error term by the Cochrane-Orcutt procedure [Cochrane and Orcutt, 1949]. Finally, the β weights were re-estimated (second stage) and tested for statistical significance by one-sided t tests (single subject level). To improve the power in the event-related design with short ISI, we included null events, which serve as a contrast condition. Therefore, we calculated the differences between the β weights of our active conditions (positive, negative, and neutral) and the contrast condition (null event). These differences were now considered as an index of activation and were tested against zero, or they were tested for differences between conditions (one-sided t tests). For both single subject and group level, significant cortical activation is indicated by positive t values for [O₂Hb] and by negative t -values for [HHb]. For one-sided t -tests, t values above 1.65 indicate an α of 5%, and t values above 2.33 indicate α of 1%. To account for multiple testing, all statistical inferences are based on an adjusted alpha level of 5%. T values over 2.84 indicate Bonferroni's adjusted α of 5% for 22 single tests (one test for each channel).

Joined EEG-NIRS Analysis

To additionally examine the associations between the EEG and NIRS in a more direct way, we chose the

Figure 1.

Displayed are the grand-mean event-related potentials over all subjects for the three conditions (positive, negative and neutral (thin line) stimuli) over the three electrode positions O1, O2, and Pz.

approach described by Eichele et al. [2005]. Within this approach we tried to predict the haemodynamic responses by the paradigm-induced amplitude modulation of the simultaneously acquired single trial ERPs. A first stimulus function was defined encoding the stimulus onset, irrespective of the condition of the stimulus. A second stimulus function encoded the onsets of the null events. Two additional stimulus functions encoded the amplitude of the single trial EPNs, one stimulus function for the positive and one for the negative condition. To get the single trial EPNs we calculated in a first step the mean EEG amplitudes for every single trial in the time window between 250 and 350 ms after stimulus presentation for all three conditions over the electrode position Oz. As the investigated EPN is calculated as the difference between emotional and neutral condition, we subtracted the mean ERP amplitudes for the neutral condition over all trials from the single trial amplitudes for the emotional condition. The stimulus functions were decorrelated (Schmidt-

Gram orthogonalization) from each other, ensuring that activation related to the amplitude modulated stimulus functions was specific to the electrophysiological measure and not to some general feature in the evoked response to the pictures. Using these stimulus functions four regressors were formed by convolving the stimulus function with the HRF (a gauss function). All further analyze steps were the same as described above.

RESULTS

ERP Results

For the EPN (Fig. 1) we found the main effects "Electrode" ($F[1.6;21.8] = 33.7, P < 0.001$), and "Condition" ($F[1.6;22.4] = 5.2, P < 0.05$), as well as an interaction effect "Electrode $\times$ Condition" ($F[2.5;34.3] = 3.8, P < 0.05$). Differences between conditions were found for all electrode positions (O1: $F[1.5;21.5] = 5.1, P < 0.05$; O2: $F[1.7;24.1] = 4.6, P < 0.05$; Oz:

Figure 2.

Changes in oxygenated haemoglobin to emotional and neutral stimuli. Displayed are the statistical maps for oxygenated haemoglobin for the second level group analyses. On the left side the activation maps for the three conditions are displayed with the corresponding t-value scale on the left side. On the top of the right side we displayed the arrangement of the measured channels. In the middle and lower right side the statistical maps for the contrasts (middle: negative versus neutral; lower: positive versus neutral) and the corresponding t-value scale are displayed.

$F[1.6;22.8] = 5.3, P < 0.05$; $Pz: F[1.6;22.9] = 5.7, P < 0.05$). For all of these positions, we found significantly higher amplitudes in the neutral than the positive and negative conditions (all t values > 2.1), without any significant differences between positive and negative condition. We calculated the EPN as the difference between neutral and positive and neutral and negative condition. The EPN amplitude did not differ for the four electrode positions (all $P > 0.1, t < 1.68$). The EPN in the positive condition also did not differ from the EPN in the negative condition (all $P > 0.2, t < 1.34$).

For the SW amplitudes we found a significant main effect “Electrode” ($F[1.9;26.42] = 14.8, P = 0.001$) and a significant interaction “Electrode $\times$ Condition” ($F[1.9;26.0] = 7.5, P < 0.01$), but no significant effect “Condition” ($F[1.9;27.1] = 2.1, P = 0.15$). Post hoc analyses revealed that conditions did not differ with respect to amplitudes for the electrode position (O1, O2, Oz, all $t < 1.2$) but only for Pz ($F[2;28] = 9.4, P < 0.001$). For Pz we found significantly higher amplitudes to negative ($t[14] = 4.1, P < 0.001$) and positive pictures ($t[14] = 3.5, P < 0.01$) compared to the neutral pictures.

NIRS Results

As expected, negative, positive, and neutral stimuli lead to a significant ($t > 2.84$) increase in $[O_2Hb]$ and corresponding decrease in $[HHb]$ within the occipital cortex (Figs. 2, 3 and 4). The increase of $[O_2Hb]$ was significant in

11 of 22 channels for negative pictures (channel nos. 5, 6, 10 to 15, 17, and 18), in 18 channels for positive pictures (no. 5 to no. 22) and in 13 channels for neutral pictures (nos. 5, 6, 8 to 15, 17, 18, and 20).

The decrease in $[HHb]$ in the same cortical regions reached a significant level ($t > 2.84$) in 16 channels for positive pictures (nos. 5, 6, 8 to 17, 19 to 22), in 18 channels for negative pictures (no. 5 to no. 22), and in 15 channels for neutral pictures (nos. 5, 6, 8 to 15, 17 to 20, 22).

We found significant ($t > 2.84$) differences of $[O_2Hb]$ between the positive and the neutral condition but not between the negative and the neutral condition. In detail, in 19 channels we measured significantly higher $[O_2Hb]$ values for positive in comparison to neutral stimuli (nos. 1, 4 to 22, all $t > 2.84$) but in no channel for the negative versus neutral comparison (all $t < 1.0$). In contrast to this, for $[HHb]$ we found that the decrease was significantly ($t < -2.84$) larger in the emotional condition compared to the neutral condition in 4 channels for the negative (nos. 9, 16, 20, and 21) and in one channel for positive pictures (no. 21, and in 4 additional channels we found corresponding trends: channel nos. 10, 12, and 13 had t values < -2.54).

Joined EEG-NIRS Analysis

With the above described joined EEG-NIRS analysis we did not find any significant associations between the am-

Figure 3.

Changes in deoxygenated haemoglobin to emotional and neutral stimuli. Displayed are the statistical maps for deoxygenated haemoglobin for the second level group analyses. On the left side the activation maps for the three conditions are displayed with the corresponding t-value scale on the left side. On the top of the right side we displayed the arrangement of the measured channels. In the middle and lower right side the statistical maps for the contrasts (middle: negative versus neutral; lower: positive versus neutral) and the corresponding t-value scale are shown.

Figure 4.

Mean and standard deviations of beta weights for the single channels. Displayed are the mean values and standard deviations of the beta weights (by the linear regression analyses) for the three conditions for each channel for oxygenated (upper) and deoxygenated (lower) haemoglobin.

plitude modulated stimulus functions and the changes in oxygenated or deoxygenated haemoglobin. Only the stimulus function encoding the onsets of the stimuli revealed the same cortical areas over the occipital cortex to be activated as in the standard analysis described above.

DISCUSSION

In this study, we found a very clear pattern of activation over the occipital cortex, with an increase in [O₂Hb] and a corresponding decrease in [HHb] during visual stimulation. The centers of activation were located in the middle of the probe set with two clear hotspots over the left and right hemisphere. The pattern of activation was very similar to the activation pattern seen from a simple visual stimulation using a checker board [Plichta et al., 2006]. Therefore, we can conclude that our paradigm of visually presenting emotional stimuli leads to an activation of the occipital cortex.

As a main result of this study, we found a modulation of cerebral oxygenation of the occipital cortex due to the emotional content of the presented visual stimuli. The decrease of [HHb] during picture processing was larger for positive as well as negative stimuli compared to neutral stimuli in regional specific areas over the occipital cortex. For the first time using simultaneous NIRS and EEG recording, results underscore that emotional stimuli increase the activity of the occipital cortex. This may due

to natural selective attention occurring while viewing pictures with an emotional content [Lang, 1997; Lang et al., 1998]. Emotional pictures are not only more interesting but also evolutionary more important and so it is more likely to attend to this kind of stimuli [Geday et al., 2003]. It has to be noted that channel no. 21, in which this modulation reached its maximum, was not in the hot spot of activation due to picture processing, but placed in the middle between both hot spots. This result indicates that the emotional content of pictures influences the brain activity to a maximum at slightly different areas than the hot spots. For the positive pictures, we found three additional channels only reaching up to a tendency, which were indeed located exactly over the hot spots (channels nos. 10, 12, and 13).

These NIRS results are in line with the ERPs derived from the simultaneously measured EEG. ERPs clearly indicated that both, positive as well as negative stimuli, led to an increased activity over the occipital cortex. The amplitudes to positive and negative stimuli were not as positive (and therefore in the difference to the neutral stimuli more negative) as those to neutral stimuli as early as 240 ms after stimulus onset. No differences in the amplitudes between positive and negative stimuli were found. With regard to the SW potential over Pz starting at 350 ms, we only found differences between positive and negative pictures in comparison to neutral (with higher positive amplitudes for emotional pictures) but no differences between positive and negative stimuli. The EEG results were in line

with previous studies [Cuthbert et al., 2000; Schupp et al., 2000, 2003], although the components looked slightly different, due to the reference position being at the tip of the nose in this experiment.

An alternative interpretation for the modulation of the occipital activation could be that possibly neutral stimuli were visually less complex than the emotional stimuli. If that would be the case, the changes in activation might be due to the differences in visual complexity of the stimuli. A recent study showed that this is not the case [Junghöfer et al., 2001]. The ERPs reflecting the processing of the emotional content of IAPS pictures were independent of formal visual properties of the stimuli like complexity.

In contrast to the similar results for positive and negative stimuli for [HHb], we had divergent findings for [O₂Hb]. Although the increase in [O₂Hb] over the occipital cortex was similar to the decrease of [HHb], the modulation of this increase due to the emotional content was only significant for positive, but not for negative pictures; we found this to be similar to our pilot study [Alpers et al., 2005a]. In the present study we could ensure that the subjects processed stimuli of both conditions in a similar way, due to the results of the ERPs. As we found a modulation of the decrease of [HHb] for both conditions, we also could assume that positive and negative stimuli did not influence the cortical activity in different areas of the occipital cortex. Therefore, it seems unlikely that the regions influenced by negative stimuli are localized deeper in the visual cortex, which might cause an inability to measure it with NIRS. One possible explanation might be that looking at positive and negative stimuli changes systemic variables in different ways. For example, it has been shown that negative pictures significantly decrease heart rate compared to neutral and positive pictures, and additionally that positive pictures lead to an increase of systolic and diastolic blood pressure compared to neutral and negative stimuli [Hempel et al., 2005; Sarlo et al., 2005]. As it has been shown that heart rate and blood pressure correlate with [O₂Hb] but not with [HHb] [Mehagnoul Schipper et al., 2000], it might be that the divergent findings for [O₂Hb] are caused by systemic variables. This means that a possibly decreased heart rate during negative picture processing reduces the increase of [O₂Hb] compared to the neutral and positive condition, but does not influence the [HHb] effects. As we did not measure heart rate and blood pressure, this interpretation is still speculative, but it should be considered in further research.

The joined EEG-NIRS analysis did not reveal any significant linear associations between the single trial ERP amplitudes and the haemodynamic responses, although this approach has been shown before to be successful [Eichele et al., 2005]. One explanation might be a methodological issue of our study design. We used very short stimulus onset intervals of 5–7 s. The power to detect significant activation within this design was increased by using null events (to be able to calculate contrasts). This approach was not possible for the amplitude modulated stimulus

function, but only for the stimulus function encoding the stimulus onset (or in the first analysis). A second problem might be that we have to calculate the difference of the amplitudes between the emotional conditions and the neutral condition to get the EPN. Therefore, the EEG amplitudes used to predict the haemodynamic responses were modulated not only by the single trial EEG response but also by the mean EEG response to the neutral stimuli.

Summing up, in this study we found indications for increased activation of the occipital cortex due to emotional stimulus processing, as indicated by ERPs as well as by a larger decrease of [HHb] measured with event-related NIRS. In the future, it might be possible to use NIRS as a noninvasive and little constraining technology to investigate the haemodynamic responses during the processing of emotional stimuli, which might be helpful in investigating the processing of disorder specific visual cues in emotional disorders such as anxiety or addiction.

REFERENCES

- Abrisqueta-Gomez J, Bueno OFA, Oliveira MGM, Bertolucci PHF (2002): Recognition memory for emotional pictures in Alzheimer's patients. *Acta Neurol Scand* 105:51–54.
- Alpers GW, Pauli P (2006): Emotional pictures predominate in binocular rivalry. *Cognit Emot* 20:596–607.
- Alpers GW, Herrmann MJ, Pauli P, Fallgatter AJ (2005a): Emotional arousal and activation of the visual cortex: A near infrared spectroscopy analysis. *J Psychophysiol* 19:106.
- Alpers GW, Ruhleder M, Walz N, Mühlberger A, Pauli P (2005b): Binocular rivalry between emotional stimuli: A validation using conditioned stimuli and EEG. *Int J Psychophysiol* 57:25–32.
- Amaral DG, Price JL, Pitkanen A, Carmichael S (1992): Anatomical organization of the primate amygdaloid complex. In: Aggleton JP, editor. *The Amygdala*. New York: Wiley. pp 1–66.
- Cochrane D, Orcutt G (1949): Application of least squares regression to relationships containing autocorrelated error terms. *Am Stat Assoc* 44:32–61.
- Cuthbert BN, Schupp HT, Bradley MM, Birbaumer N, Lang PJ (2000): Brain potentials in affective picture processing: Covariation with autonomic arousal and affective report. *Biol Psychol* 52:95–111.
- Davis M, Whalen PJ (2001): The amygdala: Vigilance and emotion. *Mol Psychiatry* 6:13–34.
- Dolcos F, Cabeza R (2002): Event-related potentials of emotional memory: Encoding pleasant, unpleasant, and neutral pictures. *Cognit Affect Behav Neurosci* 2:252–263.
- Eichele T, Specht K, Moosmann M, Jongsma ML, Quiroga RQ, Nordby H, Hugdahl K (2005): Assessing the spatiotemporal evolution of neuronal activation with single-trial event-related potentials and functional MRI. *Proc Natl Acad Sci USA* 102: 17798–17803.
- Fox PT, Raichle ME (1986): Focal physiological uncoupling of cerebral blood flow and oxidative metabolism during somatosensory stimulation in human subjects. *Proc Natl Acad Sci USA* 83:1140–1144.
- Franceschini MA, Fantini S, Thompson JH, Culver JP, Boas DA (2003): Hemodynamic evoked response of the sensorimotor cortex measured noninvasively with near-infrared optical imaging. *Psychophysiology* 40:548–560.

- Geday J, Gjedde A, Boldsen A-S, Kupers R (2003): Emotional valence modulates activity in the posterior fusiform gyrus and inferior medial prefrontal cortex in social perception. *Neuroimage* 18:675–684.
- Hempel RJ, Tulen JH, van Beveren NJ, van Steenis HG, Mulder PG, Hengeveld MW (2005): Physiological responsivity to emotional pictures in schizophrenia. *J Psychiatr Res* 39:509–518.
- Herrmann MJ, Ehlis AC, Fallgatter AJ (2003): Prefrontal activation through task requirements of emotional induction measured with NIRS. *Biol Psychol* 64:255–263.
- Herrmann MJ, Ehlis A-C, Scheuerpflug P, Fallgatter AJ (2005): Optical topography with near-infrared spectroscopy during a verbal-fluency task. *J Psychophysiol* 19:100–105.
- Horovitz SG, Gore JC (2004): Simultaneous event-related potential and near-infrared spectroscopic studies of semantic processing. *Hum Brain Mapp* 22:110–115.
- Hoshi Y (2003): Functional near-infrared optical imaging: Utility and limitations in human brain mapping. *Psychophysiology* 40:511–520.
- Hoshi Y, Shimada M, Sato C, Iguchi Y (2006): Reevaluation of near-infrared light propagation in the adult human head: Implications for functional near-infrared spectroscopy. *J Biomed Opt* 10:064032.
- Junghöfer M, Bradley MM, Elbert TR, Lang PJ (2001): Fleeting images: A new look at early emotion discrimination. *Psychophysiology* 38:175–178.
- Koizumi H, Yamashita A, Maki T, Ito Y, Itagaki H, Kennan R (1999): High-order brain function analysis by trans-cranial dynamic near-infrared spectroscopy imaging. *J Biomed Opt* 4:403–413.
- Lang PJ (1997): Motivated attention: Affect, activation and action. In: Lang PJ, editor. *Attention and Orienting: Sensory and Motivational Processes*. Mahwah, NJ: Erlbaum. pp 97–135.
- Lang PJ, Bradley MM, Fitzsimmons FR, Cuthbert BN, Scott JD, Moulder B, Nangia V (1998): Emotional arousal and activation of the visual cortex: An fMRI analysis. *Psychophysiology* 35:199–210.
- Lang PJ, Bradley MM, Cuthbert BN (1999): International Affective Picture System (IAPS): Technical Manual and Affective Ratings. Gainesville, FL: Center for Research in Psychophysiology.
- LeDoux J (1998): Fear and the brain: Where have we been, and where are we going? *Biol Psychiatry* 44:1229–1238.
- Mehagnoul Schipper DJ, Vloet LC, Colier WN, Hoefnagels WH, Jansen RW (2000): Cerebral oxygenation declines in healthy elderly subjects in response to assuming the upright position. *Stroke* 31:1615–1620.
- Obrig H, Villringer A (2003): Beyond the visible—imaging the human brain with light. *J Cereb Blood Flow Metab* 23:1–18.
- Öhman A, Mineka S (2001): Fears, phobias, and preparedness: Toward an evolved module of fear and fear learning. *Psychol Rev* 108:483–522.
- Okada E, Delpy DT (2003): Near-infrared light propagation in an adult head model. I. Modeling of low-level scattering in the cerebrospinal fluid layer. *Appl Opt* 42:2906–2914.
- Pessoa L, Kastner S, Ungerleider LG (2002): Attentional control of the processing of neural and emotional stimuli. *Brain Res Cogn Brain Res* 15:31–45.
- Phan KL, Wager T, Taylor SF, Liberzon I (2002): Functional neuroanatomy of emotion: A meta-analysis of emotion activation studies in PET and fMRI. *Neuroimage* 16:331–348.
- Plichta MM, Herrmann MJ, Baehne CG, Ehlis A-C, Richter MM, Pauli P, Fallgatter AJ (2006): Event-related functional near infrared spectroscopy (fNIRS): Are the measurements reliable? *Neuroimage* 31:116–124.
- Posner MI, Raichle ME (1995): Precis of images of mind. *Behav Brain Sci* 18:327–383.
- Sarlo M, Palomba D, Buodo G, Minghetti R, Stegagno L (2005): Blood pressure changes highlight gender differences in emotional reactivity to arousing pictures. *Biol Psychol* 70:188–196.
- Schroeter ML, Zysset S, Kupka T, Kruggel F, Yves von Cramon D (2002): Near-infrared spectroscopy can detect brain activity during a color-word matching Stroop task in an event-related design. *Hum Brain Mapp* 17:61–71.
- Schupp HT, Cuthbert BN, Bradley MM, Cacioppo JT, Ito T, Lang PJ (2000): Affective picture processing: The late positive potential is modulated by motivational relevance. *Psychophysiology* 37:257–261.
- Schupp HT, Junghofer M, Weike AI, Hamm AO (2003): Emotional facilitation of sensory processing in the visual cortex. *Psychol Sci* 14:7–13.
- Strangman G, Boas DA, Sutton JP (2002): Non-invasive neuroimaging using near-infrared light. *Biol Psychiatry* 52:679–693.
- Villringer K, Minoshima S, Hock C, Obrig H, Ziegler S, Dirnagl U, Shwainger M, Villringer A (1997): Assessment of local brain activation. A simultaneous PET and nearinfrared spectroscopy study. *Adv Exp Med Biol* 413:149–153.