INTRODUCTION

Since being introduced as a research tool, near-infrared spectroscopy (NIRS) has gained wide support and recognition among cognitive neuroscientists, despite having several disadvantages when compared with other non-invasive measurements of neural activation. For instance, NIRS has poor spatial resolution compared with other neuroimaging techniques that measure neurovascular responses, such as functional magnetic resonance imaging and positron emission tomography. Similarly, the temporal resolution of NIRS is much lower than that of electroencephalography (EEG) and magnetoencephalography. The acceptance of NIRS as a novel technique for measuring neural activation might be partly attributable to several unique characteristics. First, NIRS measurement is thought to impose a considerably less severe physical and psychological burden than that of electroencephalography (EEG) and magnetoencephalography. The acceptance of NIRS as a novel technique for measuring neural activation might be partly attributable to several unique characteristics. First, NIRS measurement is thought to impose a considerably less severe physical and psychological burden than that of existing neuroimaging techniques. Thus, this technique is particularly advantageous for measuring neural responses in the elderly and infantile populations (Ichikawa et al., 2010; Ozawa et al., 2011; Kida and Shinohara, 2013b). Second, the ease of NIRS measurement makes it a suitable technique for collecting data from a large participant cohort. Third, the measurement of neural activation using near-infrared light is, in principle, more robust with respect to exogenous noise in the environment. Thus, NIRS is considered to be a useful technique for measuring neural activation under less constrained and more ecologically valid settings, with several exceptions (Suzuki et al., 2004).

Despite having relatively poor spatial and temporal resolution, near-infrared spectroscopy (NIRS) has several methodological advantages compared with other non-invasive measurements of neural activation. For instance, the unique characteristics of NIRS give it potential as a tool for investigating the role of the prefrontal cortex (PFC) in emotion processing. However, there are several obstacles in the application of NIRS to emotion research. In this mini-review, we discuss the findings of studies that used NIRS to assess the effects of PFC activation on emotion. Specifically, we address the methodological challenges of NIRS measurement with respect to the field of emotion research, and consider potential strategies for mitigating these problems. In addition, we show that two fields of research, investigating (i) biological predisposition influencing PFC responses to emotional stimuli and (ii) neural mechanisms underlying the bi-directional interaction between emotion and action, have much to gain from the use of NIRS. With the present article, we aim to lay the foundation for the application of NIRS to the above-mentioned fields of emotion research.

Keywords: NIRS, emotion, prefrontal cortex, hemispheric asymmetry, reward, autonomic nervous system

EMOTION PROCESSING IN THE PFC

The neural mechanisms underlying emotional experience and mood have been the focus of intensive research in both the fields of cognitive neuroscience and clinical psychiatry. According to the now classic “limbic system” model (MacLean, 1949) of neural mechanisms of emotional response, evolutionally ancient subcortical structures generate primitive emotions, such as fear. Emotions originating in the “reptilian brain” are further elaborated in the diverse brain regions of phylogenetically advanced neural circuits, including the PFC. Consistent with this model,
more recent studies have identified the PFC as a key region in the induction and regulation of emotional responses (Davidson and Fox, 1982; Damasio, 1996; Rolls, 1996).

Although there is now a wealth of empirical evidence for the role of the PFC in emotion processing, the exact function subserved by this region is unclear. At the same time, there are several widely accepted views regarding the function of each subregion of the PFC, as summarized in an insightful review by Dalgleish (2004). First, the orbitofrontal region of the PFC has been closely linked to reward processing and reinforcement learning (Rolls, 1996). Specifically, the orbitofrontal PFC appears to play a pivotal role in associating exogenous stimuli with rewarding reinforcers, thereby promoting the assignment of emotional value and salience. Second, the ventromedial PFC may act as an interface between visceral reactions and higher cognitive function. This view is championed by the influential “somatic-marker hypothesis” (Damasio, 1996), which proposes that somatic markers, as peripheral reactions to stimuli, are processed in the ventromedial PFC as part of a system that guides higher order cognitive functions. Third, the “valence asymmetry hypothesis” of the PFC (Davidson et al., 1999) suggests that the motivational tendency of a living organism can be conceptualized along the dimension of approach/withdrawal. More specifically, when approach motivation is activated, an organism is strongly motivated to pursue an appetitive or rewarding goal. Conversely, the activation of withdrawal motivation emphasizes avoidance of harmful situations rather than acquisition of rewards. The core proposition of the valence asymmetry hypothesis is that the right PFC activates withdrawal motivation and the left PFC activates approach motivation, thereby enabling adaptive behaviors.

OVERVIEW OF EXISTING NIRS STUDIES

Several NIRS studies have examined the role of PFC activation in emotion processing. An overview of these findings could be beneficial for several reasons. First, the existing findings might serve as scaffolding upon which researchers could build novel experimental designs. Second, a summary of existing NIRS data might support or oppose established views about the emotional function of the PFC (Davidson and Fox, 1982; Damasio, 1996; Rolls, 1996). Although different types of hemodynamic response are frequently treated as equal [oxy-Hb] reflects different aspects of task-related hemodynamic responses from the concentration of deoxygenated hemoglobin [referred to as (deoxy-Hb)] whose change is supposed to be closely linked to BOLD response (Song et al., 2006). Therefore, a dose examination of NIRS data might produce a more comprehensive picture about neural activation during emotion processing. In the following sections, we briefly review the previous findings in light of the above-mentioned theories about the nature of emotion processing in the PFC (Davidson and Fox, 1982; Damasio, 1996; Rolls, 1996). The details about the major studies covered below are summarized in Table 1.

SENSITIVITY TO REWARDING STIMULI

As for the reward sensitivity of the PFC (Rolls, 1996), at least two studies with adult participants have found that [oxy-Hb] in the vicinity of the orbitofrontal region of the PFC increases following exposure to rewarding stimuli, such as tactile stimulation by velvet (Kida and Shinohara, 2013a) and viewing one’s own infant smiling (Minagawa-Kawai et al., 2009a). Interestingly, an analogous increase in [oxy-Hb] has also been observed in the same region in infants (Minagawa-Kawai et al., 2009a; Kida and Shinohara, 2013b), suggesting that NIRS is a suitable method for measuring reward system activation in participants of varying ages.

PROCESSING OF VISCERAL REACTIONS

Few NIRS studies to date have specifically examined the neural mechanisms mediating the influence of visceral “somatic” markers on behavior. This is partly due to a technical limitation of NIRS. The ventromedial PFC, which is considered to be the locus of integration between somatic markers and higher order cognitive functions (Damasio, 1996), is located too far from the cranium surface for accurate measurements of activation using NIRS.

With regard to the link between visceral reactions and the PFC, several NIRS studies have succeeded in revealing an association between activation of the PFC and activation of the autonomic nervous system (ANS) in response to emotional stimulation. For example, Tanida et al. (2007) reported that the degree of right-lateralized asymmetry in PFC activation patterns observed during mental stress was positively correlated with the level of activation of the sympathetic nervous system. Likewise, increased [oxy-Hb] has been positively correlated with heart rate change when viewing trauma-related video clips (Matsuo et al., 2003). Furthermore, Moghimi et al. (2012) have linked the steepness of the peak of [oxy-Hb] to a subjectively reported arousal level, which is a relatively coarse, but widely accepted indicator of ANS activation (for similar findings, see Matsuo et al., 2003; Roos et al., 2011). These studies offer partial support for the view that the PFC processes visceral reactions, or somatic markers, associated with exogenous stimuli. At the same time, these findings are mere correlational, and so caution should be exercised in interpreting such data. Furthermore, if causal relations are present, the direction of causality has yet to be clarified.

HEMISPHERIC ASYMMETRY

Many NIRS studies have used bilateral probes to measure hemodynamic responses, and thus have datasets that are suitable for examining hemispheric asymmetry in the PFC. In these studies, either one of the following criteria was adapted to judge the hemispheric asymmetry in the cortical activations: (1) the significant increase of [oxy-Hb] from the baseline in only one of the hemispheres, or (2) the significant inter-hemispheric difference in the level of [oxy-Hb] change. Several studies have produced evidence in support of the valence-asymmetry hypothesis (Moriyama et al., 2007; Marumo et al., 2009; Tuscan et al., 2013). For example, Moriyama et al. (2007) reported that anticipation of an electrical shock was associated with a greater increase in [oxy-Hb] in the right compared with the left PFC. Furthermore, increases in [oxy-Hb] in the right PFC were positively correlated with the strength of harm-avoidance tendencies in the participants. At the same time, a number of studies have failed to detect hemispheric asymmetry in task-related activation as predicted by the valence-asymmetry hypothesis (Herrmann et al., 2003; Kobayashi et al., 2007; Yang et al., 2007; Hoshi et al., 2011). Much of the empirical support for the valence-asymmetry hypothesis...
Table 1 | Summary of the findings of the major NIRS studies covered in the present review.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Task</th>
<th>Major findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kida and Shinohara (2013b)</td>
<td>Adults</td>
<td>Tactile stimulation by velvet</td>
<td>Increased [oxy-Hb] to velvet in the bilateral anterior PFC</td>
</tr>
<tr>
<td>Minagawa-Kawai et al. (2009a)</td>
<td>Mothers and her infants</td>
<td>Passive viewing of smiling faces</td>
<td>Increased [oxy-Hb] in the OFC region in response to own mother/infant’s smiling face in both mothers and infants</td>
</tr>
<tr>
<td>Kida and Shinohara (2013a)</td>
<td>3, 6, 10 month-olds</td>
<td>Tactile stimulation by wood-packed velvet</td>
<td>Bilateral increase of [oxy-Hb] in the anterior PFC by velvet stimulation only in 10 month-olds</td>
</tr>
<tr>
<td>Tanida et al. (2007)</td>
<td>Young adult females</td>
<td>Stress induction by mental arithmetic</td>
<td>Right lateralized increase in [oxy-Hb] being linked to ANS activation and skin conditions</td>
</tr>
<tr>
<td>Matsumura et al. (2009)</td>
<td>Victims of traumatic event with or without PTSD</td>
<td>Passive viewing of trauma related video clips</td>
<td>Large and long-lasting increase of [oxy-Hb] concomitant with decrease of [deoxy-Hb] in the DLPFC in victims with PTSD</td>
</tr>
<tr>
<td>Moghimi et al. (2012)</td>
<td>Adults</td>
<td>Presentation of emotional music excerpts</td>
<td>Music excerpts rated as intense induced larger peaks of [oxy-Hb] change. The sharpness of [oxy-Hb] peak was also linked to arousal and valence ratings</td>
</tr>
<tr>
<td>Morinaga et al. (2007)</td>
<td>Adults</td>
<td>Anticipation of electrical shock</td>
<td>Increased [oxy-Hb] during the anticipation of electrical shock in the right PFC</td>
</tr>
<tr>
<td>Leon-Carrion et al. (2006)</td>
<td>Adults</td>
<td>Presentation of emotional video clips</td>
<td>Pronounced gender difference in [oxy-Hb] change after the offset of emotional video clips</td>
</tr>
</tbody>
</table>

has been obtained by measuring asymmetry in EEG alpha power (Davidson and Fox, 1982; Hagmann, 2004). However, the relationship between the EEG power and transient neurovascular response (as measured by NIRS) is not straightforward. Thus, it is possible that phasic changes in [oxy-Hb] are less sensitive than EEG with respect to changes in approach/withdrawal motivation.

METHODOLOGICAL PROBLEMS IN THE APPLICATION OF NIRS TO EMOTION RESEARCH

A standardized method of analyzing NIRS signals has yet to be established. Aside from the general challenges that researchers face when analyzing NIRS data, the application of NIRS to emotion research requires additional considerations.

The first problem concerns noise caused by peripheral responses to emotional stimulation. The induction of an emotional state is often accompanied by changes in bodily state, such as the contraction of facial muscles or increased cardiovascular activity. Although mitigated by homeostatic regulation, such changes in heart rate and blood pressure could potentially mask task-related hemodynamic responses in NIRS signals. Likewise, the aerobic process of energy consumption associated with muscle contraction may induce significant changes in measurable [oxy-Hb]. Schmicklmann et al. (2010) found no systematic relationship between electromyograph signals and [oxy-Hb] during a verbal fluency task. However, the influence of peripheral responses on NIRS signals has been examined only under limited conditions. A regression analysis conducted using simultaneous measurements of NIRS signals and indicators of peripheral response, such as electromyography, heart rate, and blood pressure, could be used to exclude the influence of these factors (Schmicklmann et al., 2010).

Another problem is the temporal course of neural activation induced by emotional stimulation. Both the subjective experience of an emotion and the neural responses elicited by emotional stimulation may last longer than the stimulation itself (Leon-Carrion et al., 2007). Thus, the application of conventional pre-processing methods, such as the correction of global drift (Minagawa-Kawai et al., 2009b) by linear fitting (for example, Takizawa et al., 2008), carries the risk of eliminating important results.

This point was emphasized by Leon-Carrion et al. (2006), who reported that gender differences in cortical activation were present “after” the offset of emotional stimulation. If the researchers had corrected for global drift of the NIRS signal using the period after stimulation offset as the post-stimulation baseline, the observed gender differences may have been obscured. One potential way to address this issue is the use of subjective ratings of emotional state or ANS activation monitoring to continuously track the temporal course of emotional responses for a prolonged duration. This would enable researchers to empirically define the temporal window, and then quantify the hemodynamic responses on the basis of these data.

The third problem is the selection of the appropriate indicator of the cortical activation. In many of the previous studies, the lasting increase of [oxy-Hb] was taken as the indicator of...
In which NIRS could aid investigations of emotion processing. In the next section, we present a brief overview of potential fields of research that can be performed simultaneously while measurements of neural activation are being collected. This, in turn, limits the types of phenomena that researchers can investigate. As NIRS is robust with respect to external noise, it has potential for widening the scope of investigations of the neural mechanisms underlying the interaction between emotion and action.

CONCLUSION

Despite technical limitations, NIRS is a reliable technique for quantifying several aspects of emotional functioning in the PFC, such as sensitivity to rewarding stimuli (Rolls, 1996) and processing of visceral reactions (Damasio, 1996). There are some practical challenges when using NIRS to research emotion. However, when adequate measures are taken to address these issues, NIRS is an invaluable tool that has the potential to expand the scope of investigations about the emotional function of the PFC.

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