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A systematic review of studies that used NIRS to measure neural activation during emotion processing in healthy individuals

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Abstract

Functional neuroimaging provides an avenue for earlier diagnosis and tailored treatment of psychological disorders characterised by emotional impairment. Near-infrared spectroscopy (NIRS) offers ecological advantages compared to other neuroimaging techniques and suitability of measuring regions involved in emotion functions. A systematic review was conducted to evaluate the capacity of NIRS to detect activation during emotion processing and to provide recommendations for future research. Following a comprehensive literature search, we reviewed 85 journal articles, which compared activation during emotional experience, regulation or perception with either a neutral condition or baseline period among healthy participants. The quantitative synthesis of outcomes was limited to thematical analysis, owing to the lack of standardisation between studies. Although most studies found increased prefrontal activity during emotional experience and regulation, the findings were more inconsistent for emotion perception. Some researchers reported increased activity during the task, some reported decreases, some no significant changes, and some reported mixed findings depending on the valence and region. We propose that variations in the cognitive task and stimuli, recruited sample, and measurement and analysis of data are the primary causes of inconsistency. Recommendations to improve consistency in future research by carefully considering the choice of population, cognitive task and analysis approach are provided.

Key words: near-infrared spectroscopy; emotion; prefrontal cortex; neuroimaging; review

Altered emotional processing is characteristic in the pathophysiology of many psychological disorders, including major depressive disorder, bipolar disorder and schizophrenia spectrum disorders (Green *et al.*, 2005; Li *et al.*, 2010; Townsend and Altshuler, 2012; Earls *et al.*, 2016). An influential model developed by Mayer *et al.* (2000) posits that a set of skills combining emotional and cognitive aspects constitute emotional processing (Aguirre *et al.*, 2008). The model outlines four domains: identifying emotions (commonly referred to as emotion perception), facilitating emotions (also known as emotional experience), managing emotions (also referred to as emotion regulation), and understanding emotions (Salovey and Sluyter, 1997; Mayer *et al.*, 2001). Some researchers have suggested that emotional understanding constitutes a separate social cognitive dimension and others have proposed that emotional expression is another discreet subdomain of emotion processing (Higgins and

Bargh, 1987; Phillips and Seidman, 2008). Although the terms, definitions and boundaries of emotion processing subdomains vary widely in the literature and impede comparison of findings, most researchers agree on three domains: emotional perception, experience and regulation (Green *et al.*, 2005; Isaacowitz *et al.*, 2017). Emotion perception refers to one's ability to recognise and identify a diverse array of social cues (e.g. facial expressions, body language and vocal differences) during daily interactions. Emotional experience is the immediate subjective, physiological and behavioural reaction to an emotion-invoking event or stimulus. Finally, emotion regulation refers to the process through which individuals influence what, when and how emotions are expressed, by initiating, inhibiting or modulating their feelings, thoughts, physiological responses and behaviours.

It has been well established in previous research that early diagnosis and treatment of psychological disorders lead to improved functional outcomes (Barlati *et al.*, 2013; Zwaigenbaum *et al.*, 2015; Grant *et al.*, 2017). Nonetheless, the current assessment method of many psychological conditions, including schizophrenia and autism spectrum disorders, depends upon the initial deterioration and symptom progression before a diagnosis can be made. Therefore, researchers are always seeking potential biomarkers to aid in numerous aspects of prevention and treatment, including risk factor assessment, early diagnosis, prognosis, and treatment selection and monitoring (Woo and Wager, 2015). The advancement in neuroimaging technology has shifted researchers' attention towards developing neural-based biomarkers of cognitive impairments that underlie psychological conditions. Using functional magnetic resonance imaging (fMRI), researchers have identified several candidate biomarkers for emotion processing, including the amygdala, temporo-parietal junction, prefrontal cortex (PFC) and anterior cingulate cortex (ACC) (Nord *et al.*, 2017; Lee *et al.*, 2019). Nonetheless, several previous studies have reported poor reliability of activation during a range of emotion processing tasks (Plichta *et al.*, 2012; Nord *et al.*, 2017, 2019). Although activity in these regions has demonstrated low statistical reliability between people with mood and anxiety disorders (Nord *et al.*, 2017), a recent study by Lee *et al.* (2019) found that a 12-week social cognitive training intervention modulated functional connectivity in individuals with psychotic disorders.

NIRS is an emerging neuroimaging technique that has been increasingly used in the study of cognition over the last couple of decades. NIRS is a useful tool for non-invasively measuring haemodynamic changes in the cortical surface of the brain. It operates in relation to the haemodynamic response, whereby activated regions of the brain experience high metabolic demands and an increase in oxygen consumption (Ferreri *et al.*, 2014). This consumption of oxygen leads to an initial reduction of oxygenated haemoglobin (O_2Hb), followed by an increase in regional cerebral blood flow, which consequently elevates O_2Hb concentrations (Fekete *et al.*, 2014). NIRS capitalises on the changing optical properties in cortical tissue by emitting near-infrared light into the cortex, whereby it is either absorbed, scattered or reflected, and detecting the amount of light which is redirected back towards the skull (Irani *et al.*, 2007). Emitter optodes emanate light into the cortical tissue, while the receiver optode detects the quantity of reflected light. The level of oxygenation determines the absorption properties of haemoglobin, with activated brain regions absorbing more light owing to the higher O_2Hb levels (Fekete *et al.*, 2014).

NIRS has gained wide support and recognition among cognitive neuroscientists owing to several advantages it has over other neuroimaging techniques (Nishitani and Shinohara, 2013).

Its high ecological validity is one of the most important advantages, as it can be used in natural environments without the need for sedation or restraints and is less susceptible to data corruption from participant movement (particularly the head) (Irani *et al.*, 2007; Suda *et al.*, 2010; Fekete *et al.*, 2014). This is beneficial in studying clinical populations owing to the lower physical and psychological burden on patients and reduced need for controlling their actions (Irani *et al.*, 2007). A second advantage of NIRS is its cost-effectiveness to purchase, use and maintain relative to the more expensive fMRI and positron emission tomography (PET) approaches (Fekete *et al.*, 2014). Third, in addition to being relatively easy to use, most modern NIRS systems are portable in size, enabling them to be used in a wider variety of environments, including patients' homes or shared throughout school districts (Irani *et al.*, 2007). Other advantages of NIRS include its suitability for collecting data from larger cohorts, higher temporal resolution compared to fMRI, higher spatial resolution compared to EEG, capacity to be used in combination with other neuroimaging techniques, and its high validity and reliability (Irani *et al.*, 2007; Fekete *et al.*, 2014). Finally, NIRS has the capacity to research fields, which are difficult to examine using other neuroimaging techniques, such as in the study of linguistic or auditory topics owing to the absence of instrumental noise, different bodily states because participants are not required to lay supine or communication because NIRS is capable of measuring neural activation in multiple participants simultaneously (Irani *et al.*, 2007; Suda *et al.*, 2010).

Owing to its practical advantages over other techniques, NIRS provides an avenue for investigating the psychophysiological mechanisms of disorders characterised by emotion processing impairments (Yang *et al.*, 2019). Although NIRS has been proposed as a potential tool for risk assessment, treatment monitoring and therapeutic intervention, candidate biomarkers first need to be identified, and the reliability of NIRS for detecting them must be determined (Yang *et al.*, 2019). Numerous researchers have used NIRS to investigate neural activations during emotion processing, but findings are often contradictory. While many studies implementing a range of cognitive tasks have reported O_2Hb changes in the PFC during emotion processing (Bigliassi *et al.*, 2015; Egashira *et al.*, 2015; Gruber *et al.*, 2019), other studies have reported no significant changes in O_2Hb concentrations when measured with NIRS (Ateş *et al.*, 2017; Huang *et al.*, 2017; Lucas *et al.*, 2019). Furthermore, discrepancies in localisation and direction of neural activity also exist in the literature (Rodrigo *et al.*, 2016; Abdullayev *et al.*, 2018; Anuardi and Yamazaki, 2019). The abundance of conflicting findings poses a challenge for healthcare professionals who often lack the time to source, critically appraise and extract evidence from all relevant articles to guide their decision-making (Gopalakrishnan and Ganeshkumar, 2013). Therefore, a systematic review of the literature is warranted to synthesise, clarify and provide evidence for use in clinical practice.

To date, three reviews have examined emotion processing using NIRS. The first, a mini-review by Doi *et al.* (2013), thematically described the findings from eight studies using NIRS to examine emotion-evoked prefrontal activity. A second study by Bendall *et al.* (2016) reviewed 11 recent studies, which adopted NIRS methodology to study PFC activities during emotional experiences in both healthy individuals and several patient populations, including bipolar disorder, major depressive disorder and social anxiety disorder. The third review by Maria *et al.* (2018) examined 50 NIRS studies of passive emotion processing in infants under the age of 2 years. As far as we are aware, the present review is the most extensive systematic

review of emotional processing studies using NIRS and the first review to incorporate the domains of emotion perception and regulation. This review aimed to establish the capacity of NIRS for detecting changes in neural activations during various domains of emotion processing in healthy individuals. Before NIRS can be considered for detecting potential biomarkers, its capacity for measuring activation during emotion processing must first be assessed. If NIRS is established as an effective tool for measuring functional changes during emotion processing, future investigations can then determine whether NIRS can detect differences between patient populations and healthy control groups. After summarising and synthesising the overall findings reported in studies examining three domains of emotion processing, the current review outlines methodological limitations, recommendations for future research and clinical implications.

Methods

A systematic database search was conducted of MEDLINE (PubMed), Scopus, EMBASE and Google Scholar independently by two authors (M.W. and C.H.). Additionally, the citation lists of all relevant articles and previous reviews were screened. A combination of the following search terms was employed: near-infrared spectroscopy AND (emotion processing OR emotion perception OR emotion recognition OR emotion experience OR emotion regulation). All pertinent research papers published in English between January 2000 and January 2020 were collected and imported to a reference manager (EndNote, X9 Thomson Reuters). All duplicates were removed, along with any papers not published in English. If multiple publications and companion papers were found using the same participants, only those papers with the largest sample and most in-depth assessment were included. The titles and abstracts were firstly screened for relevance, followed by a full-text reading of the relevant articles. The literature search and presentation of results were undertaken in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines.

The Population, Intervention, Comparison and Outcome (PICO) framework was employed to establish eligibility criteria (O'Connor *et al.*, 2008). Peer-reviewed articles were only included if they met four criteria: (i) the study examined a healthy human population or included a healthy control group, (ii) a cognitive task involving some form of emotion processing (perception, experience or regulation) was administered during the NIRS measurement, (iii) the task period was compared to a baseline period or a neutral task condition, and (iv) mean oxygenated haemoglobin changes were measured as the primary outcome variable. Any studies which measured O_2Hb during a neurocognitive task and later correlated that activity with performance data on an emotion processing task were excluded from this review. Only peer-reviewed articles written in English were considered. Narratives, reviews, commentaries, reports and essays were excluded from this review; nonetheless, the reference lists were screened for relevant studies.

Extraction and analysis

Two authors (M.W. and C.H.) independently extracted data from all relevant studies using a standard pre-piloted form and later compared results, resolving inconsistencies through mediation. If the first two authors could not reach consensus, the remaining authors (D.S. and D.N.) were contacted to settle the disagreement. Thirteen variables were extracted: the size of the sample, type of participants, mean age, gender distribution, the emotion processing domain, type of control condition, NIRS system used, analysis software, cognitive task, chosen stimuli, the size and direction of O_2Hb change, probe arrangement, and the geographic location of the study. When data were not adequately reported, the corresponding author of the study was contacted and the necessary data requested. If multiple groups were reported separately in a study, only the data for the healthy control group were included in the analysis. Data were reported for each of the included studies separately and synthesised thematically. Meta-analyses of the studies could not be conducted owing to inconsistencies with the type of measurement, choice of tasks and method of analyses. Owing to the lack of standardisation between the eligible studies, analyses of outcomes were limited to descriptive synthesis. Refer to Figure 1 for a summary of the selection and screening process presented using the PRISMA flow chart.

Quality assessment

The quality evaluation of eligible studies was also independently conducted by two researchers (M.W. and C.H.) according to the outlined criteria. The Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (QATOCCS), an instrument developed by methodologists at the National Institute of Health for assessing non-randomised studies, was implemented in evaluating the quality of included articles (National Institute of Health, 2004). The instrument consists of 14 items for evaluating potential flaws in study methods or implementation, including sources of bias, confounding factors, statistical power and strength of association between variables. Owing to the nature of NIRS studies, the QATOCCS scale was adapted in several ways for this review. First, item-12 was removed as blinding of participants and assessors was not applicable to this type of research. Second, item-6 was adapted to highlight the studies, which incorporated both a baseline and neutral control condition. Finally, regarding item-7, the sufficient timeframe was interpreted as block length and set to 20 s to ensure adequate time for the haemodynamic response. The 13-item checklist was used to divide the articles into three levels: poor, fair or good quality. Good-quality studies were defined as having a score equal to or greater than 9, fair-quality studies had a score ranging from 5 to 8, while poor-quality studies were defined as 5 or less. Studies rated as poor were excluded from the review. See Supplementary materials for the quality assessment instrument and score sheet.

Results

During the initial search phase, 1736 articles from databases and 11 articles from reference lists were identified and exported to EndNote (Clarivate Analytics, USA). After removing duplicates, 1384 studies were screened for relevance by examining their titles and abstracts, narrowing the pool to 125 articles for full-text evaluation. Following the aforementioned eligibility criteria, 41 studies were excluded for several reasons, including 17 for inadequate cognitive task designs, 7 for lack of full-text availability, 6 for not reporting O_2Hb concentrations, 4 for not including a healthy control group, 4 for reusing a previously reported sample, and 3 for not measuring with NIRS during the emotion processing task. A total of 85 NIRS studies were found to meet inclusion criteria and included in the final review. A full list of included studies and their summary characteristics can be found in Table 1.
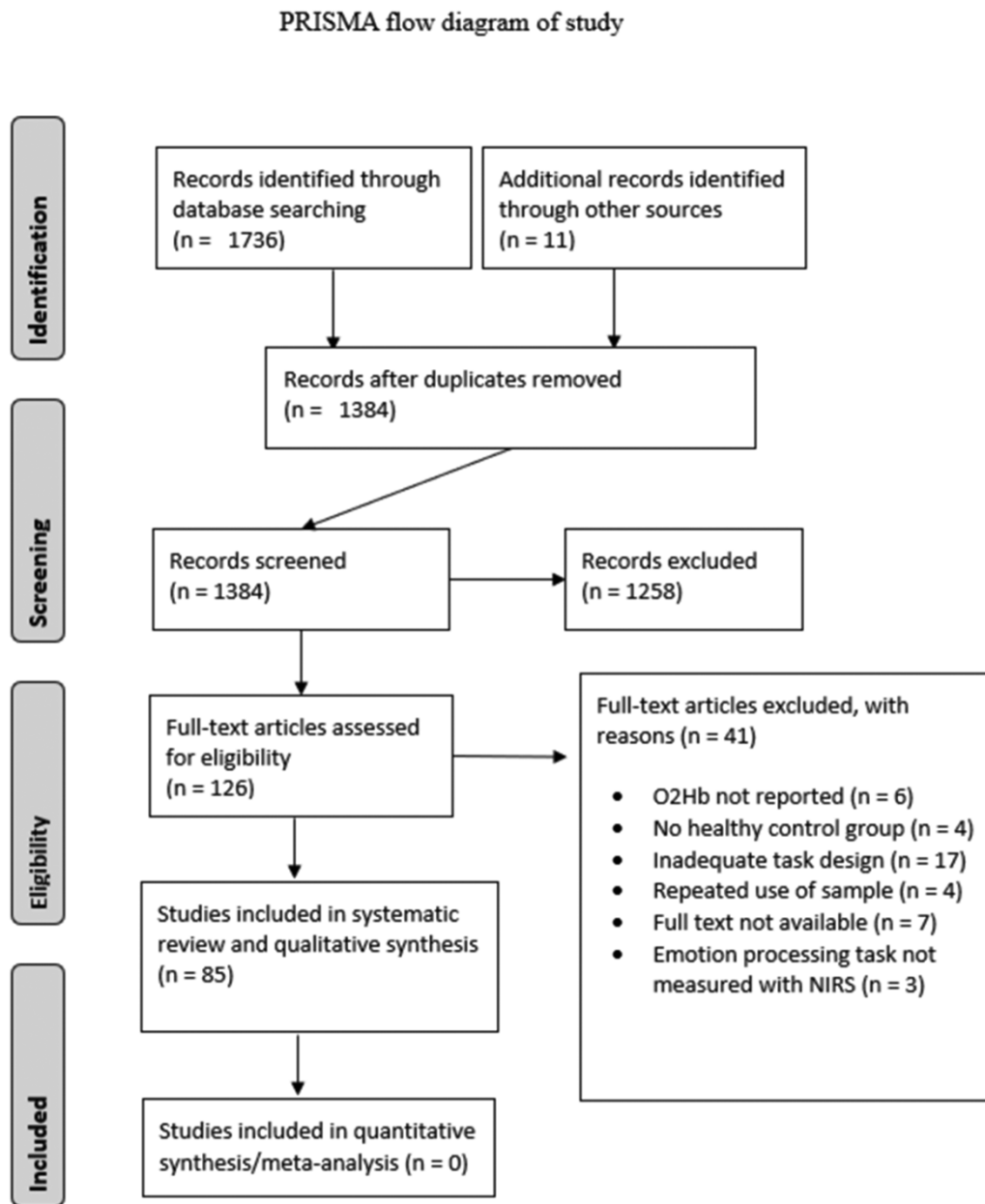
PRISMA flow diagram of study

Fig. 1. PRISMA 2009 flow diagram visually depicts the flow of studies through each phase of the review process.
Adapted from: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(6): e1000097. doi:10.1371/journal.pmed1000097.

Quality assessment

Based on the checklist criteria outlined in Supplementary Table S3, 31 of the studies were identified as good quality and 54 studies as fair quality. None of the articles maintained after screening were identified as poor quality during the quality assessment phase. Conflicts of interest were reported in one of the studies, while 39 failed to report on conflicts of interest and the remaining 45 reported that there were no notable conflicts. Attrition of participants was less than 80% in 27 of the studies. Furthermore, 25 of the studies included both a resting baseline and neutral comparison condition, which enabled better control for unrelated neurocognitive interference. A summary of the quality assessment findings can be found in Supplementary Table S2 (see Supplementary Material A).

Participant characteristics

The total sample size for the 85 included studies was 2169, consisting of 1682 healthy adults, 269 infants, 181 children and 37 elderly. Fifteen of the studies also included a clinical comparison group, including four of schizophrenia spectrum disorders, four of depressive disorders, two for autism spectrum disorders, two of ADHD and one study each for Alzheimer's, borderline personality disorder and prenatal alcohol-exposed children.

Table 1. Characteristic table for healthy control studies

Studies	Participants (n)	Location	Age, mean (s.d.)	Sex, M/F	Domain of EP (NIRS design)	NIRS system (analysis software)	Task (stimulus)	Finding (region)
Abdullayev et al. (2018)	Healthy control (24)	Turkey	32.8 (7.7)	14/10	Perception (RBP and NC, block)	ETG-4000, Hitachi	Facial Affect Identification Task (POFA)	Increased activity during task [ventral PFC and medial (m) PFC]. Reduced activity during task (dlPFC)
Anuardi and Yamazaki (2019)	Healthy adults (27)	Japan	Range 19–26	23/4	Perception (NC, block)	ETG-4000, Hitachi	Listening to emotionally toned sentences	Increased O_2Hb during neutral sounds compared to emotion (BA10 and Broca's). Increased O_2Hb during emotional condition (BA9)
Ateş et al. (2017)	Healthy control (20)	Turkey	71.35 (6.76)	9/11	Perception (RBP and NC, block)	ETG-4000, Hitachi (SPSS)	Emotional n-back task	No significant changes in O_2Hb
Balconi et al. (2015)	Healthy adults (20)	Italy	30.9 (7.99)	8/12	Experience (RBP, block)	NIRScout System, NIRx (NIRStar)	Emotional rating of picture stimuli (IAPS)	Increased O_2Hb for positive (left PFC) and negative stimuli (right PFC)
Balconi and Vanutelli (2016)	Healthy adults (14)	Italy	25.88 (2.03)	6/8	Experience (RBP and NC, block)	NIRScout System, NIRx (NIRStar)	Viewing affective pictures of human and animal interactions	Increase O_2Hb for negative human interaction (right PFC). Increase O_2Hb for positive animal interaction (left PFC)
Balconi et al. (2017)	Healthy adults (21)	Italy	27.65 (4.99)	10/11	Experience (RBP, block)	NIRScout System, NIRx (NIRStar)	Emotional rating of picture stimuli (IAPS)	Increase O_2Hb for positive (left PFC) and negative (right PFC) stimuli
Balconi et al. (2017)	Healthy adults (22)	Italy	24.5 (3.53)	10/12	Experience (RBP, block)	NIRScout System, NIRx (NIRStar)	Rating affective images of real interpersonal situations	Increase O_2Hb for positive (right PFC) compared to neutral. Greater activity for negative
Bigliassi et al. (2015)	Healthy adults (30)	Brazil	25 (2.7)	15/15	Experience (RBP, block)	MP150 System, BioPac (SPSS)	Listening to music (motivational and calm)	Increase O_2Hb during motivational and calm music (PFC, especially dlPFC). Men experienced higher (mPFC)
Brugnera et al. (2016)	Healthy adults (24)	Italy	26.1 (4.6)	12/12	Experience (RBP, block)	PocketNIRS Duo, DynaSense (MATLAB)	Recall tasks designed to elicit happiness and anger	Increase O_2Hb during positive and negative recall, particularly verbal recall (PFC)
Dieler et al. (2010)	Healthy adults (16)	Germany	28.33 (6.25)	4/12	Regulation (NC, block)	ETG-4000, Hitachi (SPM5)	Think/No-think paradigm of emotion words	Increase O_2Hb during suppression of positive and negative compared to neutral (right dlPFC and vlPFC)
Deppermann et al. (2017)	Healthy controls (23)	Germany	33.4	9/14	Experience (RBP and NC, block)	ETG-4000, Hitachi (MATLAB)	Emotional Stroop task	No significant changes between panic and neutral conditions
Di Lorenzo et al. (2019)	Healthy infants (17)	Netherlands	163.4 days	8/9	Perception (RBP and NC, block)	UCL topography half-system, NTS2 (Homer 2 and SPSS)	Facial expression recognition (fear and happiness)	Increase O_2Hb during task (occipital) and especially for the fear condition (temporal)
Egashira et al. (2015)	Healthy adults (28)	Japan	40.1 (8.1)	12/16	Perception (RBP, block)	ETG-4000, Hitachi (Integral)	Emotional go/no go (JCFEENF)	Increase O_2Hb during emotional task (left vlPFC and OFC)

(continued)

Table 1. (Continued)

Studies	Participants (n)	Location	Age, mean (s.d.)	Sex, M/F	Domain of EP (NIRS design)	NIRS system (analysis software)	Task (stimulus)	Finding (region)
Ernst et al. (2013)	Healthy adults (15)	Germany	23.4 (2.5)	7/8	Regulation (RBP, block)	ETG-4000, Hitachi (SPSS)	Virtual approach or avoid positive and negative pictures (IAPS)	Regulation of emotion images elicited increased O_2Hb. Positive caused stronger activation than negative (dmPFC)
Fanti et al. (2016)	Young adults with low callous-unemotional traits (30)	Cyprus	20.52 (1.40)	14/16	Experience (NC, block)	MP150 System, BioPac (MATLAB)	Rating valence of video clips (violent, comedy, neutral)	Higher O_2Hb for positive compared to neutral condition, while the negative resulted in reduced O_2Hb
Fox et al. (2013)	Infants at low risk for ASD (10)	USA	6.91 months	9/6	Perception (NC, block)	ETG-4000, Hitachi	Viewing movie clips of mother and strangers changing from neutral to smiling expression	Increase O_2Hb for smiling compared to neutral (right lateral and frontal regions)
Gao et al. (2019)	Healthy adults (24)	China	43.13 (11.28)	11/13	Perception (RBP, block)	CW-NIRS	Facial expression recognition (Cohn–Kanade database)	Increased O_2Hb during emotion recognition (left and right PFC) and decrease for sadness (right PFC)
Giles et al. (2018)	Healthy adults (36)	USA	24.4 (3.6)	15/21	Regulation/experience (RBP and NC, block)	NIRSport, NIRx (NIRStar)	Cognitive reappraisal task (IAPS—negative only)	Decreased activity during negative experience, increase O_2Hb during negative regulation (dorsal and APFC)
Glotzbach et al. (2011)	Healthy adults (20)	Germany	22.4 (2.17)	0/20	Regulation/experience (RBP and NC, block)	ETG-4000, Hitachi	Cognitive reappraisal task (IAPS—neutral and fearful)	Increased O_2Hb during fearful experience. Regulation was characterised by lower Hhb, but no changes for O_2Hb (PFC)
Grabell et al. (2018)	Healthy children (65)	USA	5.04 (1.3)	33/32	Regulation (RBP, block)	CW6 system, NIRSOptic (MATLAB)	FETCH task and rate mood after	Increased O_2Hb during emotion regulation (lPFC)
Grabell et al. (2019)	Healthy children (60)	USA	4.9 (0.9)	30/30	Regulation (RBP, block)	CW6 system, NIRSOptic (AnalyzIR and SPSS)	Frustration regulation task (Incredible Cake Kids) and interpersonal scaffolding	Control children showed no change in lPFC activation for negative or positive feedback
Gruber et al. (2019)	Healthy adults (28)	Switzerland	26.44 (4.7)	14/14	Perception (NC, block)	Oxymon MKIII, Artinis (MATLAB)	Categorisation/discrimination of emotional prosody for pseudowords	Decrease in O_2Hb for categorisation, discrimination and passive listening tasks. Greater decrease for fear compared to neutral condition (frontal LH)
Heger et al. (2014)	Healthy male adults (8)	Germany	27.6 (5.2)	8/0	Experience (NC, block)	Oxymon MKIII, Artinis	Valence and arousal rating (IAPS/IADS)	Decreased O_2Hb with neutral stimulus but increases with emotional stimuli. No topographical patterns (e.g. lateralisation effects) could consistently be observed
Herrmann et al. (2003)	Healthy adults (14)	Germany	31.7 (6.2)	7/7	Experience (RBP and NC, block)	NIRO-300, Hamamatsu (SPSS)	Viewing and rating of emotional stimuli (IAPS and POFA)	No significant differences for IAPS. O_2Hb increased for negative, neutral and positive POFA faces compared to pre-task baseline (LH)

Table 1. (Continued)

Studies	Participants (n)	Location	Age, mean (s.d.)	Sex, M/F	Domain of EP (NIRS design)	NIRS system (analysis software)	Task (stimulus)	Finding (region)
Herrmann et al. (2008)	Healthy adults (16)	Germany	24.2 (2.4)	5/11	Experience (NC, block)	ETG-4000, Hitachi	IAPS (positive-high arousal, negative high arousal, neutral low arousal).	Negative, positive and neutral stimuli lead to increase O_2Hb (occipital cortex). Significant differences in O_2Hb were found between the positive and neutral conditions but not between negative and neutral
Herrmann et al. (2016)	Healthy adults (28)	Germany	22.71 (4.18)	1/27	Perception (RBP, block)	ETG-4000, Hitachi	Facial emotion recognition	No significant effects were found for O_2Hb
Himichi et al. (2015)	Healthy adults (34)	Japan	20.59 (1.72)	13/21	Experience (RBP, block)	FOIRE-3000, Shimadzu (SPSS)	Infer feeling of a character playing a card game (ATR facial expression)	O_2Hb was higher for draw than lose conditions [vmPFC and left ventrolateral (vl) PFC]. Left vlPFC activation was also positively correlated with evaluations of sadness and pleasure.
Hirata et al. (2018)	Healthy controls (18)	Japan	34.5 (28–38.5)	13/5	Perception (RBP, block)	ETG-4000, Hitachi	Facial identification and emotion recognition task (JCFEENF)	Decrease O_2Hb during task condition (left frontotemporal area)
Holper et al. (2016)	Healthy controls (27)	Switzerland	29.7 (6.41)	16/11	Regulation (NC, block)	ETG-4000, Hitachi (MATLAB)	Emotional Stroop	Increase activity for negative condition (dlPFC and middle temporal gyrus)
Honda et al. (2018)	Healthy adults (11)	USA	24.6 (2.2)	11/0	Regulation (NC, block)	LABNIRS, Shimadzu (Integral)	Facial expression suppression while viewing disgust video stimuli	Increased activity for the negative condition (left PFC)
Hoshi et al. (2011)	Healthy adults (19)	Japan	Range 21–25	8/11	Experience (NC, block)	OMM-2000, Shimadzu (SPSS)	Rating emotional stimuli (IAPS)	Decrease O_2Hb for positive (left dlPFC) and increase for negative condition (vlPFC)
Hosokawa et al. (2015)	Healthy adults (38)	Japan	24.4 (3.5)Overall sample	20/18	Perception (RBP, block)	ETG-4000, Hitachi	Facial emotion recognition (ATR database)	Increase O_2Hb during negative condition only (PFC)
Hu et al. (2019)	Healthy adults (15)	China	22.5	8/7	Experience (RBP, block)	DLP, NirScan (Integral)	Viewing and rating emotion inducing videos	Increases in O_2Hb for encouragement (mPFC) and harmony (left lPFC)
Huang et al. (2017)	Healthy adults (26)	China	22.4 (2.1)	15/11	Experience (RBP and NC, block)	LABNIRS,Shimadzu (NIRS_SPM)	Rating valence and arousal of emotion-evoking images (IAPS)	No significant changes in O_2Hb were found between unpleasant and neutral conditions
Ichikawa et al. (2014)	Healthy boys (13)	Japan	9.7 (1.2)	13/0	Perception (RBP, block)	ETG-4000, Hitachi	Facial expressions recognition (FIND)	Increase O_2Hb for happy and sad faces (left and right temporal areas)
Ieong and Yuan (2018)	Healthy controls (7)	China	36.6 (10.7)	3/4	Perception (RBP, block)	CW fNIRS system (SPSS)	Emotion recognition (Mind in the Eyes)	Decrease O_2Hb during recognition compared to baseline (mPFC)
Kable et al. (2017)	Healthy children (12)	USA	11.4 (3.1)	6/6	Experience (RBP, block)	FNIRS 100B, BioPac (FNIRSoft and SPSS)	Frustration rating task (FETCH)	Increase O_2Hb in the left lPFC and mPFC (positive) and left lPFC (negative) during task condition

(continued)

Table 1. (Continued)

Studies	Participants (n)	Location	Age, mean (s.d.)	Sex, M/F	Domain of EP (NIRS design)	NIRS system (analysis software)	Task (stimulus)	Finding (region)
Kida et al. (2014)	Healthy elderly women (17)	Japan	63.7 (SE: 1.6)	0/17	Experience (RBP, block)	NIRO-200, Hamamatsu (NIRS_SPM)	Rating love for grandchildren (own vs unknown) in video clips	Increased O_2Hb while viewing own grandchild irrespective of facial expression compared to unknown child with the same expression (medial and inferior APFC)
Kochel et al. (2011)	Healthy adults (35)	Austria	23.94 (3.40)	18/17	Experience (RBP, block)	ETG-4000, Hitachi (MATLAB and SPSS)	Rating emotional pictures (IAPS)	Increased O_2Hb during disgusts and happy conditions compared to neutral (occipital region)
Köchel et al. (2013)	Healthy adults (43)	Austria	26.1 (3.59)	24/19	Experience (RBP and NC, block)	ETG-4000, Hitachi (SPM5)	Rating emotional sounds (IADS)	Increase O_2Hb during emotion task (right STG and supramarginal gyrus)
Kochel et al. (2015)	Healthy children (14)	Austria	121.93 (11.29) months	14/0	Experience (RBP, block)	ETG-4000, Hitachi (NIRS_SPM)	Reading emotional and neutral sentences (Tubinger Affect Battery)	Increase O_2Hb during anger sadness and happiness (right STG)
Kondo et al. (2018)	Healthy controls (25)	Japan	34.1 (10.1)	18/7	Experience (NC, block)	ETG-4000, Hitachi (JMP Pro12)	Emotion-related image recall task	Increase O_2Hb during positive and negative recall (bilateral frontal temporal region)
Kreplin and Fairclough (2013)	Healthy adults (30)	UK	22 (3.26)	15/15	Experience (RBP, block)	fNIR Imager1000, NIRx (fNIRSoft)	Spot the difference and emotional introspection task	Increase O_2Hb during positive condition (rostral PFC and medial BA10)
Kreplin et al. (2015)	Healthy adults (20)	UK	25.05 (7.1)	10/10	Experience (RBP, block)	fNIR Imager1000, NIRx (fNIRSoft)	Emotion rating of art images from self or other perspective	Increase O_2Hb during negative images from other perspective. Increase activity from self-perspective for positive images (rostral PFC)
Krol et al. (2019b)	Healthy infants (84)	Germany	214.07 (7.25) days	42/42	Perception (NC, block)	NIRScout System, NIRx (Nilab 2)	Passive viewing expressions (FACES collection)	Increase O_2Hb during fear and happiness conditions and decrease in anger condition (right PFC)
Leon-Carrion et al. (2007)	Healthy adults (30)	Spain	25.84 (7.62)	15/15	Experience (RBP, block)	NIMprobe, NIM Inc.	Viewing and rating emotional videos	Increase O_2Hb during task especially negative condition (dlPFC)
Lu et al. (2019)	Healthy adults (40)	China	21.5 (1.4)	20/20	Perception (RBP and NC, Block)	LABNIRS, Shimadzu (NIRS-SPM, SPM8 and SPSS)	Producing opposite facial expressions to presented faces (CFAPS)	Increased O_2Hb for positive and negative compared to neutral condition (left front and middle PFC). Decrease for positive (left pre-motor area)
Lucas et al. (2019)	Adults with low neuroticism (39)	Spain	20.65 (2.67) overall sample	0/39	Experience (RBP, block)	fNIRS 1100, Biopac (fNIRSoft)	Passive viewing of facial expressions (NimStim and Radboud)	No significant O_2Hb changes between valences (PFC). Significant interaction between valence and time (left lPFC)

(continued)

Table 1. (Continued)

Studies	Participants (n)	Location	Age, mean (s.d.)	Sex, M/F	Domain of EP (NIRS design)	NIRS system (analysis software)	Task (stimulus)	Finding (region)
Manelis et al. (2019)	Health controls (16)	USA	23.69 (3.45)	2/14	Perception (RBP, block)	CW6 system, NIRSOptic (NIRS toolbox)	Rating emotional intensity of facial expressions (KDEF faces)	Decrease activity during emotional task (dlPFC)
Marumo et al. (2009)	Healthy adults (20)	Japan	32.6 (9)	10/10	Experience (RBP and NC, block)	ETG-4000, Hitachi (SPSS)	Passive viewing fearful faces (FACS)	Increase O_2Hb (left dlPFC), Female showed greater activation than males
Matsubara et al. (2014)	Health controls (20)	Japan	41.4 (8.5)	10/10	Regulation (RBP and NC, block)	ETG-4000, Hitachi (SPSS)	Emotional Stroop task	Increase O_2Hb in regulation task (Left inferior frontal and middle frontal region)
Matsukawa et al. (2017)	Healthy adults (14)	Japan	23 (1)	7/7	Experience (RBP, block)	NIRO-200, Hamamatsu (PowerLab)	Watching and rating emotionally charged movies	Decreased O_2Hb during comedy movie and no change during horror or landscape movies (bilateral PFC)
Matsuo et al. (2003)	Healthy volunteers (12)	Japan	37.1 (11.0)	9/3	Experience (RBP, block)	ETG-100, Hitachi	Rating emotional movies	No significant changes in O_2Hb
Minagawa-Kawai et al. (2008)	Healthy mothers (18) and infants (15)	Japan	Mother: 33.1 years, Infants: 11.7 months	0/18, 8/7	Experience (RBP, block)	ETG-7000, Hitachi	Passive viewing videos (no sound) of mothers and babies with neutral and smiling faces	Increase activity during the presentation of smiling faces compared to neutral faces (frontal area)
Moghimi et al. (2012)	Healthy adults (10)	Canada	25 (2.7)	5/5	Experience (NC, block)	Imagent Functional Brain Imaging System from ISS.	Rating intensity and valence of emotional experience after listening to music excerpts	Music with positive or negative emotional content lead to increases in O_2Hb (PFC)
Morinaga et al. (2007)	Healthy adults (56)	Japan	25.2 (6.8)	32/24	Experience (RBP, block)	NIRO-300, Hamamatsu (BIMTAS-II)	Anticipation of electrical shock	Increase O_2Hb during negative task condition (right PFC)
Nakadoi et al. (2012)	Healthy controls (14)	Japan	31.5 (4.8)	6/8	Experience (NC, block)	ETG-4000, Hitachi (SPSS)	Passive viewing of fearful and neutral faces (ATR international faces)	Increase activity during the fearful compared to the neutral condition (PFC)
Nakata et al. (2018)	Young (22) and elderly (20) adults	Japan	21.7 and 70.2	-	Experience (RBP, block)	OEG-16, Spectratech	Virtual reality (VR) driving simulation. Red-light condition to elicit anger	No significant difference in O_2Hb between any conditions for young adults. Increase O_2Hb for elderly adults in red compared to other conditions (particularly in LH).
Nakato et al. (2011)	Healthy infants (12)	Japan	16.7 months (range: 6–7)	5/7	Perception (RBP and NC, block)	ETG-4000, Hitachi	Passively viewing facial expression (FIND)	Increased O_2Hb during presentation of happy (left temporal cortex) and angry faces (right temporal area)
Nishikawa et al. (2015)	Healthy adults (53)	Japan	24.05 (range: 22–37)	35/18	Perception (RBP, block)	NIRO-200, Hamamatsu (SPSS)	Facial emotion recognition (DB99)	Increased O_2Hb in LH and RH for clear, less clear and ambiguous facial emotions. RH O_2Hb was higher for ambiguous and less clear vs clear

(continued)

Table 1. (Continued)

Studies	Participants (n)	Location	Age, mean (s.d.)	Sex, M/F	Domain of EP (NIRS design)	NIRS system (analysis software)	Task (stimulus)	Finding (region)
Nishitani et al. (2011)	Healthy women (28)	Japan	28.4 (7.4) and 31.2 (5.2)	0/28	Perception (RBP, block)	OM-220, Shimadzu	Facial discrimination and emotion recognition task (infant facial expressions)	Increased activity during task period compared to baseline (PFC)
Ohtani et al. (2005)	Healthy adults (10)	Japan	40.3 (14.5)	6/4	Experience (RBP, block)	ETG-100, Hitachi	Emotional memory recall task	Increased O_2Hb during the task period compared to baseline (PFC)
Ozawa et al. (2014)	Healthy adults (20)	Japan	19.38 (0.79)	20/0	Experience (RBP and NC, block)	OEG-16, Spectratech	Valance rating of pictures and n-back task (IAPS)	Increased O_2Hb during the negative condition compared to baseline (PFC)
Ozawa et al. (2019)	Healthy adults (15)	Japan	19.91 (1.71)	25/0	Experience (RBP, block)	OEG-SpO2, Spectratech (MATLAB and SPSS)	Valance rating of pictures and n-back task (IAPS)	Reduced O_2Hb changes during task compared to baseline (vmPFC)
Perlman et al. (2014)	Healthy children (17)	USA	4.5 (36–77 m)	9/8	Experience (RBP, block)	CW6 system, NIR-SOptic (MATLAB)	Frustration rating task (FETCH)	Increased O_2Hb during Winning blocks (right middle PFC) and decrease O_2Hb in Frustration blocks (left dorsal PFC)
Piper et al. (2015)	Healthy adults (104)	USA	20.61 (18–38)	36/68	Experience (RBP, block)	fNIR Devices LLC	Rating elevating/amusing videos	No significant difference from baseline or amusement condition (mPFC)
Plichta et al. (2011)	Healthy adults (17)	Germany	25.95 (4.59)	7/10	Experience (NC, block)	ETG-4000, Hitachi (MATLAB)	Rating emotional sounds (IADS)	Increased O_2Hb in positive and negative compared to neutral condition (bilateral temporal lobes)
Ravicz et al. (2015)	Healthy infants (24)	USA	212 (1) days	13/11	Perception (NC, block)	ETG-4000, Hitachi (Homer 2 and SPSS)	Passive viewing faces (NimStim faces)	Decrease O_2Hb during task condition (PFC)
Rodrigo et al. (2016)	Healthy adults (39)	Canada	28.46 (12.09)	4/35	Experience (NC, block)	fNIR Imager1000, NIRx (SPSS)	Incidental emotion (fear) recognition during facial encoding task (gender)	Increase O_2Hb (right mPFC) and decreased (left mPFC) during the emotional task condition
Roos et al. (2011)	Healthy controls (9)	South Africa	25.3 (5.7)	0/9	Perception (RBP, block)	DYNOT System, NIRx (SPM5)	Facial emotion recognition (fear)	Increased activity for fearful stimuli compared to resting baseline (PFC)
Ruocco et al. (2010)	Healthy controls (8)	USA	18.88 (0.84)	0/8	Regulation (RBP and NC, block)	Custom developed system at Drexel University	Sadness cognitive reappraisal task (IAPS)	Higher O_2Hb during the task condition compared to the baseline (anterior frontal lobe)
Schneider et al. (2014)	Healthy adults (33)	Germany	28.9 (Range: 19–51)	10/23	Perception (RBP and NC, block)	ETG-4000, Hitachi (SPSS and MATLAB)	Emotion identification task (videos of neutral and emotionally expressive walking)	Increase O_2Hb for negative gait (right and left occipito-temporo-parietal areas)
Tupak et al. (2014)	Healthy adults (35)	Germany	26.46 (6.96)	11/24	Regulation (RBP, block)	ETG-4000, Hitachi	Threatening matching and labelling task (IAPS)	Increased activity for negative condition compared to baseline (vlPFC)
Vanutelli et al. (2015)	Healthy adults (22)	Italy	24.4 (3.57)	10/12	Experience (RBP and NC, block)	NIRScout System, NIRx (NirsLab)	Passive viewing affective pictures depicting human and animal interactions	Increase O_2Hb for aggressive human and friendly animal interactions compared to neutral. Decreased O_2Hb for aggressive animal interactions (PFC)

(continued)

Table 1. (Continued)

Studies	Participants (n)	Location	Age, mean (s.d.)	Sex, M/F	Domain of EP (NIRS design)	NIRS system (analysis software)	Task (stimulus)	Finding (region)
Wang, et al. (2018a)	Healthy adults (24)	China	22.4 (2.1)	15/11	Experience (RBP and NC, block)	LABNIRS, Shimadzu (Homer 2 and SPSS)	Rating emotional pictures (IAPS)	Increased activity during presentation of positive compared to neutral images. No changes for negative images (left dlPFC)
Wang et al. (2018b)	Healthy adults (12)	China	22.8 (1.91)	5/7	Experience (RBP, block)	CW6 system, NIRSOptic (Homer 2 and SPSS)	Anticipating emotional pictures (IAPS)	Positive condition induced higher O_2Hb compared to neutral and negative conditions (left dlPFC)
Watanabe et al. (2011)	Healthy adults (28)	Japan	21.9 (1.2)	0/28	Experience (RBP and NC, block)	ETG-4000, Hitachi (SPSS)	Passive viewing emotional pictures (IAPS)	Increased O_2Hb during emotional task especially for negative stimuli (PFC)
Watanuki et al. (2016)	Healthy controls (19)	Japan	40.53 (8.29)	9/10	Perception (RBP, block)	ETG-4000, Hitachi	Emotion face recognition task (JCFEENF)	Significant difference in O_2Hb between emotion recognition and neutral identification tasks (left mPFC and left vlPFC)
Wei et al. (2017)	Healthy controls (30)	China	28.6 (6.52)	18/12	Experience (RBP and NC, block)	LABNIRS, Shimadzu (NIRS_SPM)	Passive viewing emotional pictures (IAPS)	Decreased O_2Hb during presentation of negative and positive compared to neutral and baseline (left and right dlPFC)
Yang et al. (2007)	Healthy controls (30)	China	24.32 (1.86)	11/19	Experience (RBP and NC, block)	(SPSS)	Passive viewing neutral and negative pictures (IAPS)	Increased O_2Hb during stressful picture period for female group only (PFC)
Yu et al. (2017)	Healthy adults (7)	Singapore	36.3 (11.3)		Experience (RBP, block)	NIRSport, NIRx (NIRS_SPM)	Emotion induction video stimulus	Increase O_2Hb during emotional task period (right PFC)
Zhang et al. (2017)	Healthy infants (18)	China	39.8 (1) weeks	9/9	Experience (RBP and NC, block)	NIRScout System, NIRx (SPSS, NFRI and NirsLab)	Passive emotional prosody (DCVE)	Increased O_2Hb for fearful, angry and happy prosodies compared to neutral (right MTG, STG and supramarginal gyrus)
Zhang et al. (2018)	Healthy adults (22)	China	20.8 (0.4)	10/12	Experience (RBP and NC, block)	NIRScout System, NIRx (MATLAB)	Passive emotional prosody (DCVE)	Increase in O_2Hb for happy compared to neutral condition (left pars triangularis). No significant changes in O_2Hb for anger or fear.
Zhang et al. (2019)	Healthy infants (60)	China	39.2 (1) weeks	30/30	Experience (RBP and NC, block)	NIRScout System, NIRx (MATLAB)	Passive listening to speech samples in Chinese and Portuguese	Compare to neutral condition, higher O_2Hb for positive (right temporal and bilateral frontal regions), fearful (right temporal and parietal regions) and angry stimuli (STG)
Zhao et al. (2019)	Healthy infants (29)	China	189 (9.66) days	14/15	Experience (RBP and NC, block)	Custom built by Biomedical Optics Research Laboratory (Homer 2)	Passive listening to emotional prosody	Increased O_2Hb for angry compared to neutral (left anterior superior temporal cortex). Increased O_2Hb for happy vs angry (right posterior STC)

ASD, autism spectrum disorder; DCVE, Database of Chinese Facial Emotions; dl, dorsolateral; IAPS, International Affective Picture System; LH, left hemisphere; NC, neutral condition; OFC, orbitofrontal cortex; PFC, prefrontal cortex; POFA, pictures of facial affect; RBP, resting baseline period; RH, right hemisphere; vm, ventromedial.

Across all articles mentioning gender ($n = 1$ did not report gender), the ratio of males to females was 1006 (45.7%) to 1195 (54.3%), respectively. Four of the studies included only male participants, while eight included females only. The mean age ranged from 163 days to 63.7 years, with an average of 28.8 years (s.d. = 4.2) across all studies. The studies were conducted in a variety of countries, including 25 from Japan, 13 from China, 12 from Germany, 11 from the USA, six from Italy, three each from Austria and the UK, two from Spain, Switzerland and Turkey, and a single study from Brazil, Cyprus, Netherlands, Singapore and South Africa. Although 15 of the 85 studies also included a clinical sample for comparison, it was not a necessary criterion as group comparisons fell outside the scope of this review.

NIRS measurement and analysis

A total of 30 different NIRS systems were used to measure O_2Hb changes across the reviewed studies, including CW6 (NIRSOptic), DLP (NirScan), DYNOT (NIRx), ETG-100/4000/7000 (Hitachi), Imager1000 (NIRx), FNIR100B/1100 (BioPac), FOIRE-3000 (Shimadzu), LABNIRS (Shimadzu), MP150 (BioPac), NIMprobe (NIM Inc.), NIRO-200/300 (Hamamatsu), NIRScout (NIRx), NIR-Sport (NIRx), OEG-16 (Spectratech), OEG-SpO2 (Spectratech), OM-220 (Shimadzu), OMM-2000 (Shimadzu), Oxymon MKIII (Artnis), PocketNIRS duo (DynaSense) and eight custom-developed systems. The ETG-4000 (Hitachi, Japan) was the most common system, being used by 29 (33.7%) of the studies, followed by the NIRScout with nine (10.5%) studies. There were 43 (50.6%) articles which compared the task-related activity to a resting baseline condition, 17 (20%) which compared to a neutral or control task condition, and 25 (29.4%) examined both baseline and neutral conditions. The probes were positioned 3 cm apart for all studies and placed over the frontal lobe in 75 of the studies, temporal lobe in seven studies, occipital lobe in three studies and parietal lobe in a single study. In addition to the range of NIRS systems and probe layouts, the studies also used a variety of different softwares to analyse the NIRS data, including MATLAB, SPSS, SPM 5, SPM 8, Homer 2, NIRS_SPM, fNIRSoft, NIRStar, AnalyzIR, JMP Pro 12, NIRS toolbox, BIMTAS-II, NIRSLab, PowerLab and the integral mode of various systems.

Emotion processing outcomes

Emotional experience

Emotional experience was the most commonly examined domain of emotion processing, with 51 studies containing a total of 1286 participants. Forty-three studies focused on the PFC, while eight examined other brain regions, including the occipital cortex and temporal lobe. Of the 43 studies examining the PFC, 22 (51.2%) reported increased O_2Hb in the PFC during the experience of emotion stimuli, three (7%) reported greater activation only for negative stimuli (Herrmann *et al.*, 2003; Yang *et al.*, 2007; Ozawa *et al.*, 2014) and six (14%) reported no significant change in the O_2Hb (Matsuo *et al.*, 2003; Piper *et al.*, 2015; Deppermann *et al.*, 2017; Huang *et al.*, 2017; Nakata *et al.*, 2018; Lucas *et al.*, 2019). In contrast, three (7%) studies claimed there was a decrease in O_2Hb in the PFC during emotional experience (Himichi *et al.*, 2015; Wei *et al.*, 2017; Ozawa *et al.*, 2019). The remaining nine studies (20.9%) reported mixed findings depending on the valence or type of presented stimuli (Hoshi *et al.*, 2011; Perlman *et al.*, 2014; Vanutelli and Balconi, 2015; Fanti *et al.*, 2016; Rodrigo *et al.*, 2016; Matsukawa *et al.*, 2017; Wang *et al.*, 2018a,b; Zhang *et al.*, 2018).

Emotion regulation

Eleven studies with a total of 313 participants examined the domain of emotional regulation. Of the 11 studies, six (54.5%) reported increased activity in the PFC during regulation tasks (Dieler *et al.*, 2010; Ruocco *et al.*, 2010; Ernst *et al.*, 2013; Matsubara *et al.*, 2014; Giles *et al.*, 2018; Grabell *et al.*, 2018), three (27.3%) reported increased prefrontal activation only during the regulation of negative stimuli (Tupak *et al.*, 2014; Holper *et al.*, 2016; Honda *et al.*, 2018) and two (18.2%) studies reported no significant changes in O_2Hb (Glotzbach *et al.*, 2011; Grabell *et al.*, 2019).

Emotion perception

With a total of 600 participants, 23 studies examined the domain of emotion perception. Nineteen of the studies examined the PFC, while four focused on other regions of the temporal or occipital cortices. Of the 19 prefrontal studies, five (26.3%) reported a significant increase in PFC activity during emotion recognition tasks (Nishitani *et al.*, 2011; Fox *et al.*, 2013; Egashira *et al.*, 2015; Nishikawa *et al.*, 2015; Lu *et al.*, 2019) and two (10.5%) reported increased O_2Hb for negative stimuli only (Roos *et al.*, 2011; Hosokawa *et al.*, 2015). In contrast, five (26.3%) studies reported a significant decrease in O_2Hb (Ravicz *et al.*, 2015; Hirata *et al.*, 2018; Ieong and Yuan, 2018; Gruber *et al.*, 2019; Manelis *et al.*, 2019) and two (10.5%) reported no significant change in O_2Hb (Herrmann *et al.*, 2016; Ateş *et al.*, 2017). One study by Watanuki *et al.* (2016) declared a significant change in O_2Hb but failed to indicate the direction of change. The remaining four (21%) of studies presented mixed findings depending on the prefrontal region or type of emotion stimuli (Roos *et al.*, 2011; Abdullayev *et al.*, 2018; Anuardi and Yamazaki, 2019; Gao *et al.*, 2019).

Discussion

This review aimed to establish the capacity of NIRS for detecting haemodynamic changes during emotion processing and provide recommendations for future research to improve reliability. Following a comprehensive literature search, we identified 85 peer-reviewed journal articles assessing O_2Hb concentrations during tasks of emotion processing among healthy participants. Of the included articles, 51 studies examined emotional experience, 23 emotion perception and 11 emotional regulation. There was a wide variety of experimental paradigms across the various studies; thus, quantitative analyses of data were limited. Nonetheless, we thematically summarised and synthesised the findings, highlighted methodological limitations and made recommendations for future research. A frequency distribution of overall study outcomes is presented in Figure 2.

Emotional regulation

The findings were most consistent among studies of emotional regulation with almost all the reviewed studies showing increased O_2Hb in the PFC during the task period, especially for the regulation of negative stimuli. For example, Giles *et al.* (2018) delivered a cognitive reappraisal task using negatively valences IAPS images and found increased activities in the dorsal and APFC during the reappraisal condition. Likewise, Honda *et al.* (2018) reported increased activity in the left PFC when participants were required to suppress their own facial expressions during the presentation of negatively valenced video stimuli.
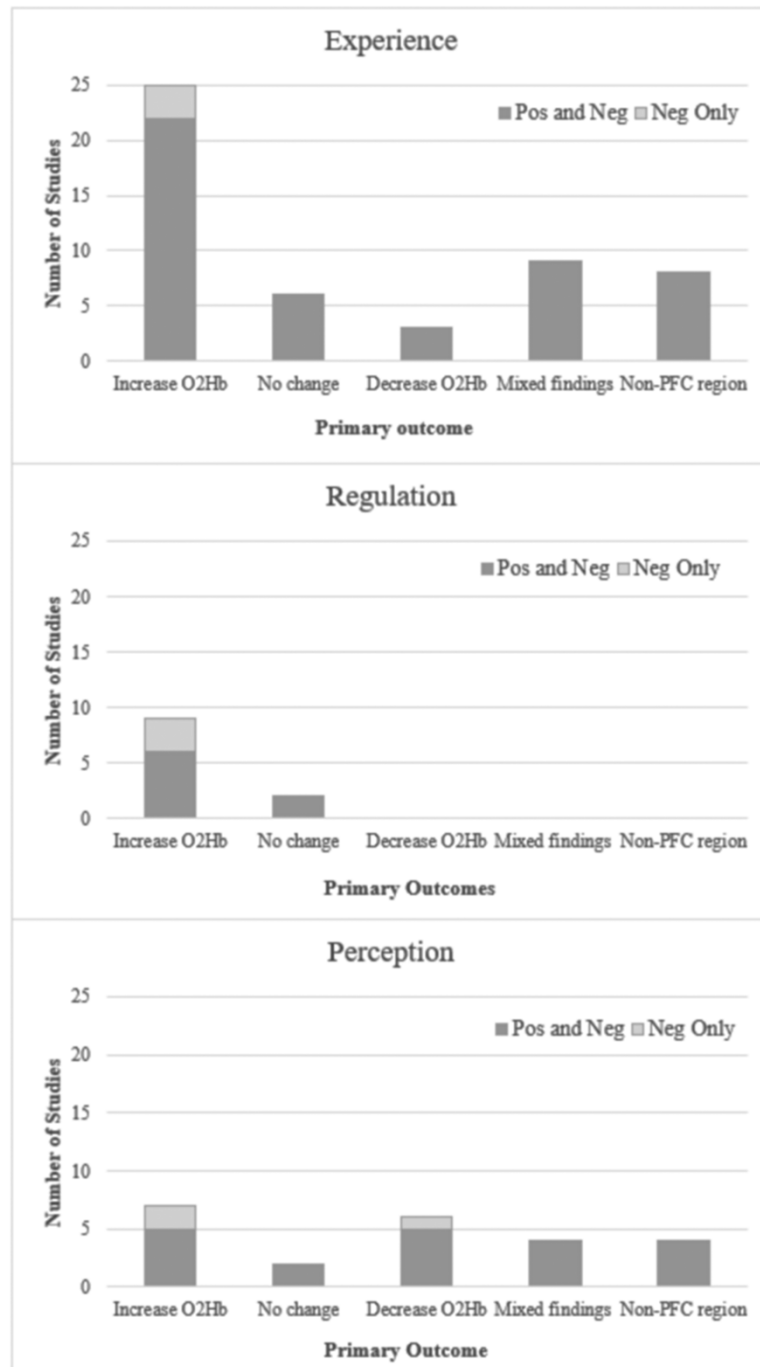
Fig. 2. Frequency distribution of study outcomes. The findings were most consistent among studies of emotional regulation with almost all the reviewed studies showing increased O_2Hb in the PFC. Many studies reported significant increases in prefrontal O_2Hb concentrations during emotional experience, but there are several studies with conflicting findings. Inconsistent findings were reported among the reviewed studies of emotional perception, with some reporting increased prefrontal activity, some decreased and other no significant changes in O_2Hb.

These findings are congruent with fMRI studies, which have found increased activation in the vlPFC, dmPFC and left superior temporal gyrus, as well as hypoactivation in the amygdala and OFC (Mak *et al.*, 2009; Grecucci *et al.*, 2012; Kohn *et al.*, 2014; Picó-Pérez *et al.*, 2017). Nonetheless, one meta-analysis of cognitive reappraisal studies found activation in the lateral temporal cortex and bilateral amygdala, but not in the vmPFC or any other region (Buhle *et al.*, 2014). Dörfel *et al.* (2014) examined various emotion regulation strategies separately and found that cognitive reappraisal recruited a qualitatively different network comprising the left vlPFC and orbitofrontal gyrus, compared to the right prefrontal–parietal region activated by other strategies, including detachment, expressive suppression and distraction. A recent meta-analysis of fMRI studies further concluded that the dmPFC, angular gyri and left vlPFC are typically activated during cognitive reappraisal of emotion (Picó-Pérez *et al.*, 2017). Taken together, these findings suggest that the left lateral PFC plays a role in constructing reappraisal strategies that can

modulate activity in emotion centres of the brain (Anderson and Green, 2001; Ochsner *et al.*, 2002; Dieler *et al.*, 2010).

Although the findings among studies of emotional regulation are relatively consistent, limited research has examined this domain of emotion processing ($n = 11$ studies), task dimensions varied widely, and studies were often limited by statistical power, sensitivity and generalisability. Specifically, three articles only focused on a single type of emotion (Ruocco *et al.*, 2010; Glotzbach *et al.*, 2011; Honda *et al.*, 2018), three only examined negatively valenced stimuli (Ernst *et al.*, 2013; Tupak *et al.*, 2014; Giles *et al.*, 2018), three used word-based interference tasks involving neurocognitive interference (Dieler *et al.*, 2010; Matsubara *et al.*, 2014; Holper *et al.*, 2016), and the remaining two studies used developmentally appropriate paradigms suitable only for young children (Grabell *et al.*, 2018, 2019). To date, there have been no NIRS studies of emotional regulation using a range of emotional stimuli to evoke affective states in healthy functioning adults. Future research should focus more attention on the domain of emotion regulation by using representative samples and comprehensive tasks to verify the findings presented in the reviewed studies.

Emotion experience

The experience of emotion was by far the most extensively researched domain of emotion processing. Many studies reported significant increases in prefrontal O_2Hb concentrations during the presentation of emotionally inducing stimuli (Kreplin and Fairclough, 2013; Brugnera *et al.*, 2016; Balconi *et al.*, 2017; Hu *et al.*, 2019; D. Zhang *et al.*, 2019). Several studies also reported increased activity in other brain regions, including the occipital cortex during visual tasks (Herrmann *et al.*, 2008; Köchel *et al.*, 2011) and the temporal lobe for tasks of auditory modality (Plichta *et al.*, 2011; Kondo *et al.*, 2018; Zhao *et al.*, 2019). Nonetheless, although most studies agreed on the increased O_2Hb concentrations during emotional experience, no significant changes were found by others (Nakata *et al.*, 2018; Lucas *et al.*, 2019) and some even reported decreased prefrontal O_2Hb concentrations during the presentation of emotional stimuli (Himichi *et al.*, 2015; Wei *et al.*, 2017; Ozawa *et al.*, 2019). These findings are congruent with fMRI studies, which have linked parts of the PFC to emotional experience, even though there is no consensus on the exact role, localisation and nature of activation (Kober *et al.*, 2008; Wacker *et al.*, 2009; Gazzaniga and Ivry, 2013; Green *et al.*, 2015). One meta-analysis of fMRI and PET studies suggests that there is no single region that uniquely represents emotional valences, but rather valence is flexibly implemented across instances by a set of valence-general regions, including the anterior insula, rostral vmPFC, dorsal ACC, amygdala, ventral striatum, thalamus and occipitotemporal cortex (Lindquist *et al.*, 2016).

Investigators have proposed that different neural systems are responsible for the processing of different emotions (Gazzaniga and Ivry, 2013). Providing support for this theory, neuroimaging studies have revealed that activation in brain networks varies depending on the emotional situation (Chang *et al.*, 2015; Kragel and LaBar, 2016). It is possible that alteration in neural activities between some of the reviewed studies may reflect differences in the types or valences of emotional stimuli presented. A theme was uncovered in several reviewed studies whereby positively valenced stimuli were characterised by O_2Hb increases in the left hemisphere and negatively valenced stimuli in the right hemisphere (Balconi and Vanutelli, 2016; Balconi *et al.*, 2017; Wang *et al.*, 2018a). This pattern of activity is consistent with two general theories of hemispheric asymmetry

for emotion: the right hemisphere hypothesis and the valence hypothesis. The right hemisphere hypothesis posits that the activation in the left hemisphere may function to regulate the intensity of activation in the right hemisphere, whereby overactivation is associated with negative experiences and underactivation is associated with positive experiences. In contrast, the valence hypothesis of hemispheric asymmetry suggests that the anterior portions of both hemispheres are differentially specialised, with the left side being more dominant for positive experiences and right-side dominance for the experience of negative emotions. Although there is considerable evidence to support both theories, the extent to which either hemisphere is involved remains unclear. Nonetheless, these findings suggest that, even within the PFC, positive and negative emotions are characterised by different patterns of activation. Although this is consistent with our findings, some of the studies with conflicting results implemented tasks with a limited emotional range (Himichi *et al.*, 2015; Nakata *et al.*, 2018). Thus, further research is needed into the experience of different types of emotion using NIRS.

Researchers have suggested that the resolution of NIRS might be too coarse to discriminate between different emotional processes (Glotzbach *et al.*, 2011). Although previous fMRI studies have shown reliable differences in prefrontal activation between emotional experience and regulation (Ochsner *et al.*, 2002; Lévesque *et al.*, 2003; Kalisch *et al.*, 2005; Phan *et al.*, 2005; Banks *et al.*, 2007; Eippert *et al.*, 2007), it remains unclear how well NIRS can distinguish between the difference cognitive states. One fMRI study found that cognitive reappraisal activates prefrontal regions similar to those reported in studies of emotion regulation, while emotional experience activates the bilateral amygdala (Winecoff *et al.*, 2011). It has been theorised that the PFC plays a role in suppressing activity in the amygdala during emotional regulation, which can result in detectably greater haemodynamic activity in the PFC and lower activation in the amygdala during emotional regulation compared to experience (Glotzbach *et al.*, 2011). Despite the coarseness and low spatial resolution of NIRS, initial studies have shown different patterns of activation for emotional regulation and experience. For example, Giles *et al.* (2018) found decreased activity in the dorsal and APFC during negative experience and increased activity during negative regulation. Similarly, Glotzbach *et al.* (2011) found increased O_2Hb in the PFC during fearful experience and no significant change during emotional regulation.

Emotion perception

Inconsistent findings were also reported among the reviewed studies of emotional perception. Many of the publications reported increased activity in PFC (Roos *et al.*, 2011; Schneider *et al.*, 2014; Egashira *et al.*, 2015; Nishikawa *et al.*, 2015), several suggested decreased activity (Ravicz *et al.*, 2015; Hirata *et al.*, 2018; Ieong and Yuan, 2018; Gruber *et al.*, 2019; Manelis *et al.*, 2019) and some reported no change in O_2Hb (Herrmann *et al.*, 2016; Ateş *et al.*, 2017). Furthermore, several of the reviewed studies reported mixed findings depending on the brain region or type of emotion being measured. Although heterogeneous emotional mechanisms likely accounted for some of these inconsistencies, discrepant findings also persisted among studies implementing similar paradigms. For example, most perception-based studies employed a photo-visual facial expression recognition task, yet patterns of prefrontal activity still varied across these studies. One study by Abdullayev *et al.* (2018) reported that O_2Hb increased in the vPFC and mPFC and decreased in the dlPFC during a facial affect recognition task.

Another study by Gao *et al.* (2019) implemented a similar recognition task and found increased O_2Hb concentration in the right PFC during the presentation of happy and fearful stimuli, while sad facial expressions resulted in decreased activity in the left PFC. Herrmann *et al.* (2016) also examined healthy adults using a facial emotion recognition task and found no significant change in O_2Hb.

These findings are congruous with fMRI research, which has identified a plethora of regions responsible for facial expression recognition, including the mPFC, fusiform gyrus, ACC, inferior frontal gyrus (IFG), superior temporal sulcus (STS), nucleus accumbens, amygdala, insula and parts of the occipital lobe (O'Doherty *et al.*, 2003; Grill-Spector *et al.*, 2004; Habel *et al.*, 2010; Dolcos *et al.*, 2011; Filkowski *et al.*, 2017). Although activity in the fusiform gyrus, amygdala, IFG, STS and occipital lobe has been found in the study of neutral faces, it seems emotion-induced activation depends upon the type and intensive of expression (Kesler-West *et al.*, 2001; Gur *et al.*, 2002; Jehna *et al.*, 2011). Angry faces have been found to elicit activation in the superior frontal gyri and ACC, while disgust has been found to elicit activation in the fronto-orbital cortex and insula, and sad faces elicit relatively greater activation in the putamen and IFG (Kesler-West *et al.*, 2001; Abel *et al.*, 2003; Fusar-Poli *et al.*, 2009; Jehna *et al.*, 2011; Wabnegger *et al.*, 2015). The mPFC has also been implicated in the processing of emotions, including happiness, fear and angry (Kesler-West *et al.*, 2001). Nonetheless, findings within the mPFC are inconsistent with some fMRI studies reporting hypoactivation, some reporting hyperactivation, and others reporting no activation (Haxby *et al.*, 2002; Vuilleumier and Pourtois, 2007; Li *et al.*, 2010; Sabatinelli *et al.*, 2011; Ruiz *et al.*, 2013). A meta-analysis of emotion activation studies using fMRI and PET found no consistent pattern of activity in PFC across individual emotions or induction methods (Phan *et al.*, 2002). Several researchers have suggested that the mPFC may be implicated in cognitive functions, which are implicit to the emotional tasks, such as directing visual attention towards facial features, especially the eyes, during emotional expression (Kesler-West *et al.*, 2001; Wolf *et al.*, 2014).

Although further investigation is needed to establish the causes of discrepancy among previous studies and to identify the most suitable approach to measuring emotion processing with NIRS, by examining differences between prior studies, we can posit several potential factors which may influence research outcomes. Three key areas of the experimental design might explain the discrepancies in research outcomes between the reviewed studies: (i) the cognitive task, (ii) the recruited sample and (iii) the methods for measurement and analysis of NIRS data. In examining the cognitive task, we will focus on variations in the intensity of stimuli, emotional valences of stimuli and type of control condition. During the discussion on the recruited sample, we will examine the effects of age and gender distribution, as well as the size of the sample. Finally, for the measurement and analysis of NIRS data, we will discuss the different types of NIRS systems, analysis software and probe arrangements.

Variations in cognitive tasks

The design of the cognitive task was a likely factor influencing research outcomes and contributing to discrepancies between studies. Many studies implemented a rating or response type paradigm whereby participants had to actively select a fixed or subjective response option, while other studies simply involved passive viewing of static images. The various task designs involved diverse cognitive demands, required a variety of neurocognitive skills, and included a range of different valances, sensory modalities and levels of complexity. The findings from this review highlighted three task design characteristics, which could potentially influence outcomes: (i) intensity of the stimuli, (ii) emotional valence of stimuli and (iii) type of control condition.

Intensity of the stimuli. Altered O_2Hb concentrations have been observed in tasks with varying degrees of complexity. Some studies presented obvious stimuli over a prolonged period, while many other studies elected for a rapid presentation of subtle expressions of emotion. One study by Gruber *et al.* (2019) provided participants with a series of semantically meaningless words spoken with various inflections and required the participants to either categorise or discriminate them based on their emotional or linguistic context. The findings revealed that, compared to a neutral condition, O_2Hb concentrations decreased in the frontal left hemisphere during categorisation and discrimination of emotional tones, especially in the fear condition (Gruber *et al.*, 2019). Another perception-based task in a study by Krol *et al.* (2019a) merely involved the passive viewing of emotional facial expressions and found increased O_2Hb in the PFC during the recognition of fear and happiness. Nishikawa *et al.* (2015) used NIRS to investigate the effect of task difficulty on neural activation during an emotional facial expression recognition task and found higher O2Hb concentrations in the right hemisphere when stimuli were more ambiguous compared to those that were less evident. In addition to highlighting the difficulties in comparing results between studies, these examples show the importance of task selection when undertaking NIRS research by demonstrating that prefrontal activity varies depending on the cognitive demands of the task.

Valence or type of emotional stimuli. Many studies have found contrasting O_2Hb concentrations amongst a range of different emotions and valences. Krol *et al.* (2019b) presented infants with emotional facial expressions and found increased O_2Hb in the right PFC during the passive viewing of happy and fearful faces but decreased activation during the presentation of anger. Another study found increased O_2Hb during passive listening to happy emotional prosody compared to the neutral condition but reported no significant activation changes for the anger or fear conditions (Zhang *et al.*, 2018). Hoshi *et al.* (2011) used a simple image valence rating task and found decreased activity in the left dlPFC for positive stimuli and increased O_2Hb in the vlPFC during the presentation of negative stimuli. Another similar study requiring participants to rate emotional images found increased O_2Hb concentrations in the left PFC for negative stimuli, but not for positive (Herrmann *et al.*, 2003). Taken together, these findings add to the growing evidence that patterns of neural activity differ according to the discrete emotion or valence of presented stimuli. Therefore, researchers risk diminishing signal reliability and contaminating data if they fail to isolate discrete emotions during analysis, owing to potential oxygenation saturation or weakening of activation by averaging across unrelated blocks. In conducting research using NIRS, it is important for investigators to include and isolate the effects of positive, negative and neutral conditions, or preferably examine each type of emotion separately. These more comprehensive approaches would allow for a more even comparison between studies and more precise findings regarding the haemodynamic changes during emotion processing.

Type of comparison condition. Alternatively, the choice of comparison condition might help explain the mixed results among reviewed studies. Many of the studies used a resting baseline period, usually consisting of viewing a cross hair on a blank screen. Other studies implemented various neutral control tasks, which provided matching cognitive demands without the emotional component. For example, a study by Fanti *et al.* (2016) presented participants with either violent, comedic or neutral video clips and found increased O_2Hb during positive videos and reduced activity during negative videos compared to the neutral condition. Another study by Nakadoi *et al.* (2012) presented images of faces displaying either fearful or neutral expression and found increased O_2Hb concentrations in the PFC during the fearful condition compared to the neutral facial expressions. On the other hand, there have been several similar studies comparing emotional experience to a resting baseline period and finding no significant changes in prefrontal O_2Hb (Matsuo *et al.*, 2003; Piper *et al.*, 2015; Matsukawa *et al.*, 2017; Nakata *et al.*, 2018; Lucas *et al.*, 2019). Without a neutral control condition, studies run the risk of detecting activation stemming from neurocognitive processing, including selective attention, visual perception and working memory. Thus, it is reasonable to assume that patterns of activation would differ between studies depending upon the type of control condition that was implemented. Owing to a lack of standardisation in the analysis and reporting of data among the reviewed studies, it is difficult to compare between the two control conditions. Although some studies included both a resting baseline and a neutral condition, to the best of our knowledge, no study has yet compared activation between the two control conditions. Future studies would benefit by examining neural activity during both resting baseline and neutral control conditions to help disentangle the influence of emotion processing from unrelated non-emotional neurocognitive processes.

Variations in the recruited sample

Previous research has established that individual differences between participants can impact on O_2Hb concentrations, especially concerning the subjective tasks used in emotion processing research (Hoshi *et al.*, 2011). For example, the mood of an individual at the time of measurement might influence their performance and associated neural activity in a manner unrelated to the task. A review by Bendall *et al.* (2016) examined 11 studies of emotional experience and argued that there were often discrepancies between individual- and group-level findings. Bendall *et al.* (2016) concluded that to reduce the likelihood of Type I and II errors resulting from systemic physiological fluctuations, future research would benefit by examining the data of individual participants before commencing a secondary-level analysis. The current review highlighted three characteristics of the recruited samples, which may have influenced the study outcomes: (i) gender distribution, (ii) age difference and (iii) the size of the recruited sample.

Gender distribution. The assumption that women are more emotional than men has transpired over the last several decades, resulting in many studies of gender difference in emotion (Parkins, 2012; Deng *et al.*, 2016). While there is substantial evidence to suggest gender differences exist across a range of emotional processes, no consensus has been reached for any specific domain as findings are often contradictory (Whittle *et al.*, 2011; Deng *et al.*, 2016). Advancements in neuroimaging have

provided an opportunity for the objective measurement of the neural mechanisms underlying emotion processing (Gross and Thompson, 2007). Studies employing fMRI or PET have found evidence for gender differences in the neurobiological mechanisms underlying emotion processing, suggesting that men and woman use different strategies when processing emotion, which can lead to diverse subjective and behavioural responses (Whittle *et al.*, 2011).

To date, few studies of emotion processing have adopted NIRS in the investigation of gender differences. Bigliassi *et al.* (2015) examined gender difference in emotional experience and found that males had significantly higher O_2Hb concentration in the mPFC while listening to motivational and calm music than females. Another study examined gender differences during passive viewing of fearful faces and found that female experienced greater activation in the left dlPFC (Marumo *et al.*, 2009). Although most studies have recruited roughly equivalent distributions of males and females, several studies restricted their focus to a single gender. Lucas *et al.* (2019) examined emotional experience using a passive viewing task in a sample of only women participants and found no significant differences in prefrontal O_2Hb. Another study focusing only on male participants employed a similar task and reported increased O_2Hb during the presentation of negative stimuli (Ozawa *et al.*, 2014). Anuardi and Yamazaki (2019) recruited a predominately male sample and found increased O_2Hb during an emotion perception task, while another similar article reported no significant O_2Hb changes among a sample of predominately female participants (Herrmann *et al.*, 2016). Taken together, these findings suggest that prefrontal brain activities during emotion processing are more prevalent among male participants than female participants. Therefore, it is possible that results could be diluted from the inclusion of more female participants owing to a potential gender effect. Nonetheless, further research directly comparing the two genders while controlling for confounding factors is warranted before such conclusions can be made.

Age differences. NIRS has been used to examine emotion processing in participants of varying ages, including infants, children, adults and the elderly. One study has investigated differences in emotional experience between younger and older adults using a VR driving simulation task (Nakata *et al.*, 2018). Nakata *et al.* (2018) discovered that elderly adults experienced increased O_2Hb in response to anger elicited by red traffic lights, while the younger adults had no significant changes in the activation for any of the traffic light conditions. Research on children populations has also produced some contrasting findings. For example, one study by Grabell *et al.* (2019) investigated emotional regulation in a sample of 60 children (mean age: 4.9 ± 1) and found no significant O_2Hb changes in the lateral PFC during either positive or negative conditions. To date, almost all studies of emotional regulation have produced consistent findings, namely increased activity in the PFC, meaning the article by Grabell *et al.* (2019) is one of the two with discrepant results. These limited findings provide some indication that the neural mechanisms underlying emotion processing, as revealed by NIRS, vary between child, adult and elderly populations.

Size and representativeness of the sample. Additionally, the sample sizes for most of the reviewed articles were quite small, with only 13 studies recruiting >35 participants and 21 studies recruiting <15 participants. Smaller sample sizes may contribute to low statistical power and reduce the reliability of

research findings (Zhang and Roeyers, 2019). For example, studies by Yu *et al.* (2017) and Heger *et al.* (2014) recruited relatively small samples ($n = 7$ and $n = 8$, respectively) and found increased prefrontal activity during an emotional experience task. Conversely, studies by Lucas *et al.* (2019) and Piper *et al.* (2015) recruited moderate to large numbers ($n = 39$ and $n = 104$, respectively) of participants relatively and found no significant changes in O_2Hb during emotion experience tasks. It is possible the studies with smaller sample sizes are finding significant results because of Type I error (Button *et al.*, 2013). The discrepancy between studies might be resolved simply by recruiting more participants to achieve sufficient statistical power.

Furthermore, a secondary issue with small sample sizes is that they are often not representative of the target population. Larger sample sizes are advantageous because they allow for more precise estimates of mean values, are usually more representative, provide a smaller margin of error and have greater generalisability (Biau *et al.*, 2008). Samples which lack representativeness are usually not generalisable and may contribute to another source of inconsistency to research outcomes (Gobo, 2004). Several of the studies included in this review used convenience sampling to recruit solely undergraduate university students. Although student samples are typically recruited because of their accessibility, low cost of administration and lower response bias, they are usually considered to be homogenous and not representative of the general population (Arnett, 2016; Hanel and Vione, 2016). As students typically represent a proportion of the population with higher socioeconomic status, educational attainment and intelligence, it raises concerns regarding the representativeness, generalisability and comparability of the results (Greenfield, 2014; Hanel and Vione, 2016). Therefore, larger more representative samples are encouraged in future research to ensure reliability.

Variations in the measurement and analysis of NIRS data

Variability in the measurement and analysis of haemoglobin concentrations was another area, which potentially contributed to the reported discrepancies. Many of the reviewed articles used different NIRS systems, probe layouts, analysis software and approaches to data pre-processing. Although each of these methods provides an accurate indication of haemodynamic changes, technical variations could lead to slight differences in research findings. Three areas of data collection and analysis were identified as potential causes of the inconsistent conclusions: (i) type of NIRS systems, (ii) selection of probe placement and (iii) choice of analysis approach and software.

Different types of NIRS systems. The use of 30 different NIRS systems might also help explain some of the inconsistencies between studies. NIRS systems use a variety of wavelengths to monitor changes in haemoglobin concentrations, which can contribute to the unreliable quality of signals (Gervain *et al.*, 2011). For example, a study by Watanabe *et al.* (2011) found increased O_2Hb in the PFC during the passive viewing of positive and negative IAPS stimuli, while another study by Wei *et al.* (2017) found decreased O_2Hb. Both studies used the same task, same stimulus materials and roughly similar samples recruited from a similar location and age group; however, the former study used a Hitachi-4000 system (NIRx) with two near-infrared wavelengths (695 nm and 830 nm) to measure haemoglobin concentrations, while the latter used a LABNIRS system (Shimadzu)

with three wavelengths (780 nm, 805 nm and 830 nm). Although it would be unreasonable to conclude the difference in findings is totally due to the use of different NIRS systems, it does provide a possible explanation for the discrepancy.

Data analysis methods and software. As NIRS is an emerging technique, there is currently no standardised approach to data analysis. Several different software packages have been developed to assist in the pre-processing and analysis of NIRS data, but most of these are either incomplete or adapted from other neuroimaging techniques. A study by Huang *et al.* (2017) analysed data using NIRS_SPM toolbox (BISP KAIST, Korea), a MATLAB-based software package that was initially designed for the statistical analysis of fMRI data and adapted for NIRS. The study used an emotional image rating task and found no significant changes in O_2Hb between positive and neutral stimuli. Another study analysed data using Homer-2, a second-generation set of MATLAB scripts explicitly designed for use with NIRS, and found increased O_2Hb in the left dlPFC during the emotional experience of positive compared to neutral stimuli (Wang *et al.*, 2018a). As with the different NIRS systems, the varying analysis approaches only serve as a possible explanation for discrepancies between studies. Future research would need to investigate and compare the various methods of data analysis to establish their consistency and identify the best approach to use in the analysis of NIRS data.

Region of interest and probe placement. The source–detector separation, number of channels and placement location are all parameters which contribute to the type of data collected. The separation between the source and detector probes determines the depth of penetration, while the quantity and position of the channels determine the amount and location of brain coverage. NIRS has limited spatial resolution compared to fMRI, and subsequently, researchers are presented with a challenge when identifying the specific brain regions, which contributed to detected changes in haemoglobin. Often the international 10–20 system, a method for mapping electrodes in EEG research, is used to localise the probe positions on a standard template. However, this method can be inaccurate because the relationship between the external probe placements and the internal brain structures is often unknown owing to the variation in head shape and size between participants.

Most of the studies included in this review focused on the prefrontal area, which is not surprising owing to the suitability of NIRS for measuring cortical tissue, the verified role of the PFC in emotion processing and the possibility of hair interference. Nonetheless, studies implementing emotion prosody tasks identified the temporal cortex as a key area of activation owing to its involvement in the auditory network (Zhang *et al.*, 2017, 2019; Zhao *et al.*, 2019). For example, a study by Zhao *et al.* (2019) found increased O_2Hb in the left anterior superior cortex during passive listening of anger-based prosody. In contrast, other studies using visual perception tasks focused on the occipital cortex (Herrmann *et al.*, 2008; Köchel *et al.*, 2011; Di Lorenzo *et al.*, 2019).

Not only should researchers carefully consider the positioning of probes, but also how they approach the grouping of channels and mapping of brain structures. Several of the studies presented in this review reported varying results depending on the examined subregion or hemisphere of measured brain structures. For example, a study by Abdullayev *et al.* (2018) exploring emotional perception found increased activity in the vPFC and

mPFC, but decreased activity in the dlPFC during a facial affect identification task. Another study reported decreased O_2Hb in the left dlPFC for positive stimuli and increased activity in the vlPFC for negative stimuli during an emotional experience rating task (Hoshi *et al.*, 2011). These studies demonstrate how even the slightest change in probe position can lead to diverse results. Over the last two decades, fMRI has been used extensively in the mapping of brain function in many areas of cognition. Investigators planning to use NIRS in their research should address relevant fMRI research before carefully selecting their approach to data collection and analysis.

Strengths and limitations of the review

The present review has several advantages. Foremost, a search of four high-quality databases resulted in a wide breadth and depth of studies from 16 countries, investigating a range of participants and using a variety of tasks. Another major strength was that two authors independently conducted the literature search, data extraction and quality assessment before consolidating their findings. Additionally, all included studies were assessed for quality using a well-established checklist tool and found to be of moderate or high quality. Finally, both studies with a resting baseline period and neutral task condition were included in this review.

Nonetheless, there were also several limitations which need to be addressed. First, very few studies have focused on the domain of emotion perception and even fewer examined emotion regulation, thus it is difficult to draw strong conclusions across these domains. Second, quantitative analyses of data were limited in this review, owing to the lack of standardisation between studies. The variations in cognitive tasks, measurement methods and approaches to data analysis not only lead to a lack of consistency between studies but also render meta-analyses difficult (Parker *et al.*, 2013). Furthermore, data extraction was constrained by the availability of the reported outcome variables. Even though care was taken to remove studies using repeated samples, it is difficult to rule out the possibility of participant data being used repeatedly across multiple papers involving the same authors. There was also a possibility of file drawer effects, which were difficult to address in this review owing to the variation between study designs. Finally, although any articles rated as weak were removed after the quality assessment stage, the included studies cannot be considered equality valued. The cognitive task designs varied considerably in terms of their complexity and depth. For example, some studies examined a range of emotions using a variety of engaging tasks, while other studies merely focused on the passive viewing of a single valence.

Recommendation for future research

Researchers should consider several aspects of the experimental design when investigating emotion processing using NIRS, including the valence, intensity and modality of the stimuli, the size and representativeness of the recruited sample, and the methods of measurement and data analysis. As outlined in this review, a lack of procedural standardisation not only made it difficult to compare findings across studies but was also a likely cause for much of the inconsistent results. It is recommended for future studies to include multiple cognitive tasks designed to measure across various emotion processing domains and sensory modalities to help explore task-related

differences and resolve inconsistent findings. Perhaps more importantly, it is recommended that future research examines a diverse array of stimuli with varying levels of arousal, intensity and valence. Neuroimaging studies have provided evidence that there are distinct brain regions or neural circuits associated with the processing of different emotions (Gazzaniga and Ivry, 2013). Furthermore, previous research suggests that the strength of activation is dependent on the level of arousal or intensity of stimuli. Thus, restricting the focus to general emotion processing may limit and potentially weaken findings, as well as make it difficult to compare across studies. It would be useful for future researchers to employ a range of stimuli with both subtle and obvious depictions of positive and negative emotions or examine discrete types of emotion (e.g. anger and happiness).

It is recommended that researchers recruit larger and more representative samples to increase statistical power and improve reliability (Zhang and Roeyers, 2019). A statistical power analysis using Faul, Erdfelder, Lang, and Buchner's (2007) G*power program 3.1 was performed for sample size estimation. Effect sizes were extracted and averaged across reviewed studies with sample sizes greater than $n = 20$ when sufficient data were provided (Balconi *et al.*, 2015; Himichi *et al.*, 2015; Piper *et al.*, 2015; Grabell *et al.*, 2019; Lu *et al.*, 2019; Lucas *et al.*, 2019). The average effect size reported in these studies was 0.34 for regulation, 0.32 for experience and 0.29 for perception. Using a two-tailed *t*-test between means with 80% power and an alpha of 0.05, the projected minimum total sample size needed with these effect sizes is approximately $n = 70$ for studies of regulation, $n = 79$ for experience and $n = 96$ for studies of perception. Thus, it is recommended that future studies should recruit a minimum of between 70 and 96 participants to ensure adequate statistical power when investigating emotion processing when using similar study methodology to that used in prior research. Furthermore, studies should recruit participants from a diverse range of education levels, socio-economic positions and cultural backgrounds to ensure the findings are generalisable to the wider population. Finally, as neuroimaging research necessitates smaller sample sizes owing to greater cost and time demands, researchers should carefully consider the type of sampling method (e.g. stratified, purposive sampling, etc.) they use to ensure the appropriateness and representativeness of their sample.

One advantage of NIRS is that it can easily be used in conjunction with other neuroimaging techniques (Bendall *et al.*, 2016). As such, future research is encouraged to use a multimodal approach to obtain more information about participants from multiple perspectives. For example, MRI could provide an anatomical–functional co-registration to assist NIRS with overcoming issues of lower spatial resolution and limited anatomical mapping (Zhang and Roeyers, 2019). Additionally, to bring about greater standardisation, future studies should compare activation during an emotional task condition with both a resting baseline period and a neutral control condition. Analysing and reporting the findings in relation to both of these control conditions would enable better comparison between studies and help disentangle emotion processing–related changes from the task-related neurocognitive influences. It is advisable for researchers to report all findings even if they are non-significant as this can help portray the true effectiveness of NIRS.

Finally, before NIRS can be considered for real-world applications, further research needs to examine the test–retest reliability to establish whether the outcomes are reliable over time

or whether they are influenced by extraneous day-to-day factors, such as a participant's mood or the amount of sleep they received during the prior night. Although some preliminary studies have found the test–retest reliability of NIRS in emotion processing to be acceptable at the group level for mapwise and clusterwise scales, further research is needed to gain better insight into the reliability of the method (Huang *et al.*, 2017). Given that existing literature has reported inconsistent findings, it remains to be seen whether the stability of O_2Hb signals is influenced by extraneous factors, such as the cognitive task, method of data processing and analysis, or the type of NIRS system and associated wavelengths (Huang *et al.*, 2017). Future research should investigate whether these factors influence the reliability of NIRS at multiple time intervals (e.g. hours, weeks or months) before we can draw more instructive conclusions.

Implications and conclusion

The diagnosis and treatment of psychological disorders stand to benefit from the development of cheaper and easier neuroimaging technology. Compared to other neuroimaging techniques, NIRS is cost-effective, makes data collection of large samples more achievable and is favourable in the study of otherwise difficult populations, including infants or patients with schizophrenia, owing to the reduced psychological discomfort and flexibility of head movement. These notable advantages advocate in favour of NIRS over other more established techniques for the purpose of real-world applications, as it would be a feasible and efficient method of biomarker screening and guided treatment of psychological disorders. Nonetheless, our findings suggest the larger samples ($n = 70$–96) required to reduce sources of noise and improve power might preclude NIRS as a sensitive enough instrument for measuring biomarkers. Further research is needed to determine the effectiveness and reliability of NIRS for measuring the neural systems involved in emotion processing.

NIRS also has a potential treatment application through neurofeedback training. Neurofeedback training would enable patients to monitor their own functional activity and use real-time feedback to regulate their neural and behavioural performance (Zhang and Roeyers, 2019). The use of neurofeedback in the treatment of a wide range of psychological conditions has already been well established using electroencephalogram (EEG) (Hurt *et al.*, 2014; Micoulaud-Franchi *et al.*, 2014). Several studies have also applied NIRS in the therapeutic intervention with some promising results. One study by Liu *et al.* (2017) used neurofeedback during a facial recognition task among ASD patients and found that those who received real-time feedback on their O2Hb showed more behavioural improvement compared to the patients who received sham feedback. Although the initial findings are promising, several limitations currently prevent NIRS from being able to compete with EEG in this regard, including the time-consuming haemodynamic response, individual difference in O_2Hb concentrations, and the lack of standardisation in measuring and analysing NIRS data.

Overall, the evidence presented in this review provides some support for the capacity of NIRS in detecting O_2Hb changes during emotion processing. Although further research is needed, the initial findings from this review highlight the lPFC as a candidate biomarker for emotional experience and regulation. Nonetheless, some studies yielded mixed results, some were limited in their design and some had outcomes that were contingent on other factors, such as the valence or intensity of stimuli. Although significant activation was found for all three domains, further research is warranted to investigate the discrepant findings reported by some studies. Several components of the experimental design were highlighted through our review of the literature, which might explain the unreliable results, including the valence, intensity and modality of the stimuli; the size and representativeness of the recruited sample; and the measurement and analysis of the data. Overall, the findings from this review show potential for NIRS to be adopted as a tool for the assessment of emotion processing impairment; however, further research is needed to address the conflicting findings between studies and establish a more reliable experimental paradigm.

Supplementary data

Supplementary data are available at *SCAN* online.

Conflicts of interest

The authors have no conflicts of interests to disclose.

Financial disclosure

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