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fNIRS An Emerging Technology for Design: Advantages and Disadvantages

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ABSTRACT

fNIRS is a functional neuroimaging technology that measures activations according to the oxygenation and deoxygenation of neural activities. A technique still little used within design, but that can contribute in neurodesign and affective, for example. Although emotions are universal, their way of perceiving and feeling is individual. The emotion design has some gaps, namely the lack of mastery of techniques and knowledge of human responses to emotions. In total, 44 articles were analyzed in a non-systematic way, with the aim to find the advantages and disadvantage of using fNIRS. As conclusion, it was possible to perceive that the fNIRS is a promising neuroimaging technique with 20 advantages points and 13 disadvantages points. The stimuli can be sensorial, cognitive and motor, handled in laboratory, in social environments or in real situations. fNIRS is already used in studies of emotions and can help to investigate the brain activations in the face of emotion processing and the affective design, enabling the possibility to design better experiences, products, services or environments focused on this affective parameter in front of neurocognition. fNIRS is an emerging and promising technique, which can help to understand some gaps in human beings as promote pleasure and well-being.

Keywords: fNIRS, Neuroimaging techniques, Neurodesign, Emotions, Neurocognition

INTRODUCTION

fNIRS (functional near infrared spectroscopy) is a wearable optical technology (Anderson *et al.*, 2020) for functional neuroimaging, based on the neurovascular coupling, which can be wired or wireless (Quaresima & Ferrari, 2016). The technology measures the change in the concentration of oxygenated (O2Hb) and deoxygenated (HHb) hemoglobin (red blood cell protein that transports oxygen) from the cortical microcirculation blood vessels, using specific wavelengths (Scholkmann *et al.*, 2014; Adorni *et al.*, 2016; Quaresima & Ferrari, 2016; Pinti *et al.*, 2018; Grazioli *et al.*, 2019; Vanutelli *et al.*, 2020). It is important to highlight that this is an indirect measure of metabolic activity (Balardin *et al.*, 2017) and that fNIRS does not measure absolute levels of O2Hb, but its concentration change (Propper *et al.*, 2016; Unni *et al.*, 2017), so the modified Beer-Lambert law is used (Unni *et al.*, 2017).

The technology works due to the dispersion of light from the NIRS, which captures the change in light intensity in view of the concentration of oxy and desoxy hemoglobin. By measuring both O2Hb and HHb, it provides a more complete assessment of cortical hemodynamic response (Quaresima & Ferrari, 2016; Descorbeth *et al.*, 2020). The technique takes advantage of the transparency of intermediate biological tissues (bones and skin) and the property of hemoglobin, as it is a selective absorber of light in the near infrared part of the spectrum (Balardin *et al.*, 2017). In addition, fNIRS is highly sensitive to haemodynamic fluctuations (Balconi & Molteni, 2015). The lights form a banana-shaped region, through optodes (one emitter and the other detector) that must be at a distance of 2 to 3 cm in adult heads and 4 to 5 cm in children's heads (Quaresima & Ferrari, 2016). It has been used to detect blood flow activity in the human PFC (Prefrontal cortex) (Doi *et al.*, 2013; Adorni *et al.*, 2016; Balada *et al.*, 2019), but neurocognitive investigation has also been highlighted (Anderson *et al.*, 2020; Balconi & Fronda, 2020), sensory, motor and observational tasks (Balconi *et al.*, 2017a; Balconi & Fronda, 2020). Balconi and Vanutelli (2017) also add that fNIRS seems to be suitable for the study of "temporally evolving representation and integration among complex, extended neural networks, of the empathic response", in addition to application in emotional and social fields (Balconi & Molteni, 2015).

fNRIS allows the analysis of changes in regional cortical activation, and this area is related to emotions (Doi *et al.*, 2013; Balconi & Vanutelli, 2016; Balconi & Vanutelli, 2017). Its use in emotion processing studies is emphasized by some authors (Doi *et al.*, 2013; Balconi & Molteni, 2015; Balconi, Vanutelli, 2017; Gruber *et al.*, 2020). Balconi and Molteni (2015) state that the activation of several cortical areas has already been verified, in the PFC, in the sensory areas and in the visual cortex in the face of emotional processing, and emphasize the research of emotions, especially in studies involving the dynamic pattern, such as facial expressions or auditory stimulation.

It has already helped in the development of interfaces to promote a better experience and usability (Bosworth *et al.*, 2019) and contributed to the advancement of understanding the functioning of the human brain in responses to emotional stimuli (Balconi & Molteni, 2015). That said, affective design aims to study how external stimuli evoke internal emotions in human beings and how this information can be understood and measured (Helander *et al.*, 2015). Johnson and Wiles (2003) correlate affective-positive with usability. In turn, Norman (2008) attests that the emotional system changes the way the cognitive system operates, which interferes with creativity and problem solving. Under the classical view, emotions are universal for human beings. However, there is an independence of the emotional state from the emotional experience itself. (Barrett, 2016). A search was carried out in 12 design magazines, looking for something related to fNIRS and only 3 articles were found, where one contained application, another mentioned the tool and the third was a bibliographic review, demonstrating the little use still in the scope of design. In view of this, the objective of this work is to investigate the advantages and disadvantages of technology for use in design, with an emphasis on affective design.

METHODOLOGY

In total, 34 articles researched on the Brazilian education platform CAPES (which includes papers from Scopus, Springer, DOAJ, among other platforms) were analyzed with the filter of the words "fNIRS" and "affective", in the last 5 years, plus a selection of 12 design journals, searching for the word "fNIRS", without time limit. The focus was on papers with applications of the technology in human beings or bibliographic references. The investigation analyzed the technical advantages and disadvantages in view of their applicability. Complete research was done in 12 design journals, but only 3 articles were found with the search for "fNIRS", one of them only mentioned the technique, another was a bibliographic reference and only one applied the technology in a product creation process. However, what it just mentioned had no material to enter the analysis, leaving only two of these papers (Izquierdo-Reyes *et al.*, 2017; Milovanovic *et al.*, 2021). When reading the articles, another 7 references considered important were added (Irani *et al.*, 2007; Doi *et al.*, 2013; Piper *et al.*, 2014; Scholkmann *et al.*, 2014; Balconi & Molteni, 2015; Quaresima & Ferrari, 2016; Pinti *et al.*, 2018). In total, there were 43 papers. The articles were read and what each author rated as advantages and disadvantages of using fNIRS was selected, analyzed and concatenated.

RESULTS

After analyzing the articles, it was to create two groups: advantages and disadvantages. Referring to the **advantages**:

1. **Portability** (Irani *et al.*, 2007; Balconi & Molteni, 2015; Quaresima & Ferrari, 2016; Ruocco *et al.*, 2016; Balconi & Vanutelli, 2017; Izquierdo-Reyes *et al.*, 2017; Bandaraa *et al.*, 2018; Burns *et al.*, 2018; Balada *et al.*, 2019; Hu *et al.*, 2019; Balconi & Fronda, 2020; Vanutelli *et al.*, 2020). Is due to the use of optical light (Burns *et al.*, 2019) in addition to the continuous advance of decreasing recording systems (Crivelli & Balconi, 2017);
2. **Movement's tolerance/Natural Movement** (Quaresima & Ferrari, 2016; Balardin *et al.*, 2017; Balconi *et al.*, 2017; Balconi *et al.*, 2017b; Crivelli *et al.*, 2018; Bandaraa *et al.*, 2018; Pinti *et al.*, 2018; Balconi & Fronda, 2020; Gruber *et al.*, 2020; Pinti *et al.*, 2021). This more natural movement stands out when compared to other neuroimaging techniques such as fMRI (Balconi *et al.*, 2017; Crivelli *et al.*, 2018; Bandaraa *et al.*, 2018; Gruber *et al.*, 2020), EEG (Crivelli & Balconi, 2017; Crivelli *et al.*, 2018) and PET (positron emission tomography – Crivelli *et al.*, 2018). Balconi *et al.* (2017) and Crivelli and Balconi (2017) justify that this more natural movement is due to lighter physical restrictions and psychological-physiological burdens compared to other techniques such as EEG and fMRI (Crivelli & Balconi, 2017);
3. **Non-invasive** (Irani *et al.*, 2007; Doi *et al.*, 2013; Scholkmann *et al.*, 2014; Balconi & Molteni, 2015; Quaresima & Ferrari, 2016; Balardin *et al.*, 2017; Balconi & Vanutelli, 2017; Crivelli *et al.*, 2018; Bandaraa

et al., 2018; Balada *et al.*, 2019; Grazioli *et al.*, 2019; Anderson *et al.*, 2020; Descorbeth *et al.*, 2020; Vanutelli *et al.*, 2020);

4. **Less onerous** (Irani *et al.*, 2007; Piper *et al.*, 2014; Gruber *et al.*, 2020; Adorni *et al.*, 2016; Quaresima & Ferrari, 2016; Ruocco *et al.*, 2016; Crivelli & Balconi, 2017; Izquierdo-Reyes *et al.*, 2017; Lloyd-Fox *et al.*, 2017; Burns *et al.*, 2018; Burns *et al.*, 2019; Hu *et al.*, 2019; Gruber *et al.*, 2020);
5. **Silent** (Quaresima & Ferrari, 2016; Balconi & Vanutelli, 2017; Zhang *et al.*, 2017; Grazioli *et al.*, 2019; Shimamura *et al.*, 2019; Vanutelli *et al.*, 2020);
6. **Not impose physical constraints** (Balconi *et al.*, 2017b; Balconi &Vanutelli, 2017; Vanutelli *et al.*, 2020);
7. **Resilient to noise - less sensitive to external noise sources** (Adorni *et al.*, 2016; Balardin *et al.*, 2017; Bandaraa *et al.*, 2018). fNIRS is less sensitive to external sources of noise, this allows participants to interact in everyday social situations (Adorni *et al.*, 2016). This converges to what Balconi *et al.* (2017) on the natural movement of participants and that technology is a good method to investigate complex movements in a more ecological context;
8. **Robustness** (Balardin *et al.*, 2017; Hu *et al.*, 2019). For Hu *et al.* (2019) robustness is related against motion and electrical artifacts;
9. **Easy applicability** / usability (Crivelli & Balconi, 2017; Rösch *et al.*, 2021; Balconi & Molteni, 2015; Lloyd-Fox *et al.*, 2017);
10. **Real-life situation | Ecological context | Realistic ambient** (Quaresima & Ferrari, 2016; Crivelli & Balconi, 2017; Balconi *et al.*, 2017; Rojiani *et al.*, 2018; Anderson *et al.*, 2020; Milovanovic *et al.*, 2021);
11. **Less time for the preparation** (Adorni *et al.*, 2016);
12. **Safe** (Irani *et al.*, 2007; Zhang *et al.*, 2017; Balada *et al.*, 2019);
13. **Minimal Risk** (Descorbeth *et al.*, 2020);
14. **High temporal resolution** (Irani *et al.*, 2007; Piper *et al.*, 2014; Quaresima & Ferrari, 2016; Ruocco *et al.*, 2016; Balconi *et al.*, 2017b; Balconi & Vanutelli, 2017; Xie *et al.*, 2018; Shimamura *et al.*, 2019; Gruber *et al.*, 2020; Milovanovic *et al.*, 2021). The temporal resolution has a rate of 100 Hz, while the normal one varies from 1 to 10 Hz (Quaresima & Ferrari, 2016);
15. **Spatial resolution** (specific spatial localization) (Balconi *et al.*, 2017b; Balconi & Vanutelli, 2017; Lloyd-Fox *et al.*, 2017; Crivelli et al., 2018; Xie *et al.*, 2018; Bosworth *et al.*, 2019; Milovanovic *et al.*, 2021). Balconi & Vanutelli (2017), Crivelli *et al.* (2018) and Balconi & Molteni (2016) discuss how fNIRS' spatial resolution is better than EEG. However, there is divergence in the qualification of the adjective. Some authors (Balconi *et al.*, 2017b) say that it is a good resolution, for Xie *et al.* (2018) it is a high resolution and for Bosworth *et al.* (2019) it is excellent when compared to EEG. The spatial resolution of fNIRS is around 1 cm (Quaresima & Ferrari, 2016);
16. **Simultaneous recording** (hyperscanning) (Balconi & Molteni, 2015; Crivelli & Balconi, 2017; Rojiani *et al.*, 2018; Fronda & Balconi, 2020; Zheng *et al.*, 2020). About hyperscanning, this is an advantage of the

tool, as it can be easily complemented by other techniques (Crivelli & Balconi, 2017);

17. **Ecological validity** (Irani *et al.*, 2007; Crivelli & Balconi, 2017; Crivelli *et al.*, 2018; Xie *et al.*, 2018; Balardin *et al.*, 2017; Balconi *et al.*, 2017b);
18. **Speaking or interaction with other people** (Pinti *et al.*, 2018; Fronda & Balconi, 2020; Zheng *et al.*,; 2020; Pinti *et al.*, 2021);
19. **High experimental flexibility** (Balconi & Molteni, 2015; Quaresima & Ferrari, 2016);
20. **Clinical utility** (Irani *et al.*, 2007; Grazioli *et al.*, 2019; Ruocco *et al.*, 2016; Rösch *et al.*, 2021).

Advantages of fNIRS become clearer when compared to other neuroimaging technologies - such as functional magnetic resonance imaging (fMRI - Shimamura *et al.*, 2019). For Lloyd-Fox *et al.* (2017) and Crivelli and Balconi (2017) the comparison of usability, cost, and spatial resolution is already with EEG (Electroencephalogram) and for this reason it has been gaining ground with lactating women and babies. The most affordable cost is also scored by Burns *et al.* (2018; 2019) in face of fMRI, in addition no to need operational costs, electricity or expertise. This helps the scientific community to choose this neuroscience technology. Its advantages, such as low cost, usability, noninvasive, resistance to movements and portability allow its use in children, less developed countries (Gruber *et al.*, 2020), in people with syndromes such as ADHD (Attention Deficit Hyperactivity Disorder) and attention deficit hyperactivity disorder (Grazioli *et al.*, 2019), in children (Lloyd-Fox *et al.*, 2017; Grazioli *et al.*, 2019), in infants (Lloyd-Fox *et al.*, 2017), in neonates (Lloyd-Fox *et al.*, 2017; Zhang *et al.*, 2017), among others. Lloyd-Fox *et al.* (2017) still evidences the benefit for babies and lactating women by the advantage of the specific spatial localization compared to EEG. Furthermore, Balardin *et al.* (2017) explains that the reason for the equipment being non-invasive is related to the principle of the technique that quantifies the migration of light through detectors positioned on the scalp. The **disadvantages** mentioned were:

1. **Relatively low spatial resolution** (Balconi & Molteni, 2015; Adorni *et al.*, 2016; Burns *et al.*, 2019; Zheng *et al.*, 2020; Rösch *et al.*, 2021). Low spatial resolution is reported by some authors (Piper *et al.*, 2014; Burns *et al.*, 2019; Gruber *et al.*, 2020) in a comparison with fMRI;
2. **Low temporal resolution** (Boas *et al.*, 2004, Adorni *et al.*, 2016; Bandaraa *et al.*, 2018, Zheng *et al.*, 2020). Zheng *et al.* (2020) and Boas *et al.* (2004) state that the low spatial resolution can generate two problems with the use of fNIRS, namely: (1) measuring only the cerebral outer cortex and (2) the uptake channels can collect brain activities from the same brain regions. What is reaffirmed by Rösch *et al.* (2021) when he states that "potentially precludes inferences on closely located brain regions". In addition, Balconi and Molteni (2015) emphasize that this low spatial resolution is when compared to other neuroimaging techniques;
3. **The head coverage is determined by the number of optodes** (Pinti *et al.*, 2021).

4. **Cap uncomfortable for long periods** - is above 30 minutes (Pinti *et al.*, 2021);
5. **Baseline need.** It occurs because the technology measures the change in oxygenation, and therefore it needs a baseline for comparison (Propper *et al.*, 2016);
6. **Social behaviors could be strongly affected** because of the visibility of the equipment (Pinti *et al.*, 2015; Quaresima & Ferrari, 2016);
7. **Unable to provide information about brain structure for anatomical reference** (Quaresima & Ferrari, 2016);
8. **Color (hair or skin) attenuate NIRS light.** (Balconi & Molteni, 2015; Propper *et al.*, 2016; Quaresima & Ferrari, 2016);
9. **Time-consuming procedure** (Balconi & Molteni, 2015; Quaresima & Ferrari, 2016). The placement of multiple sources/detectors (in particular on the hairy scalp) is time consuming (Quaresima & Ferrari, 2016);
10. **No standardization is available for fNIRS** (Quaresima & Ferrari, 2016; Milovanovic *et al.*, 2021). That is a lack of statistical validation and data standardization for analysis (Quaresima & Ferrari, 2016);
11. **High sensitivity to haemodynamic fluctuation in the scalp** Handling the equipment, such as the contact pressure between the optodes and the scalp, can change, but there are already ways to reduce this setback, such as probes with springs (Balconi & Molteni, 2015);
12. **Physiological NIRS noise.** Balconi and Molteni (2015) note that physiological NIRS noise in studies of systemic emotions can occur in some clinical conditions, such as anxiety disorder;
13. **Measure Hb concentration changes in upper cortical áreas - deep brain regions can not be investigate** (Adorni *et al.*, 2016; Bandaraa *et al.*, 2018; Rojiani *et al.*, 2018; Burns *et al.*, 2019; Balconi, Fronda, 2020; Phillips *et al.*, 2020; Vanutelli *et al.*, 2020; Zheng *et al.*, 2020; Pinti *et al.*, 2021). Phillips *et al.* (2020) states that fNIRS has an average penetration of 2.5 cm, which only allows the capture of gray brain tissue from adults, but cannot penetrate deeper tissue, such as the subcortical regions (where the amygdala is), cortical regions in deep fissures and cortical regions on the underside of the brain (Burns *et al.*, 2019). For this reason, it is used for PFC structures (Adorni *et al.*, 2016). However, this depth value is presented by Quaresima & Ferrari (2016) with an average penetration of 1.5 cm and by Milovanovic *et al.* (2021) of 3 cm;

FINAL CONSIDERATIONS

Understanding the advantages and disadvantages of the tool allows better strategic planning and greater control over what to expect and where to act on weaknesses. Balconi and Vanutelli (2017) address the combination of techniques to complement the analysis of brain activation, such as the use of EEG with fNIRS. It was possible to perceive a divergence when the point is the spatial and temporal resolution of fNIRS. This can be justified by some authors (Piper *et al.*, 2014; Burns *et al.*, 2019; Gruber *et al.*, 2020) when they mention that the spatial resolution is lower than that of fMRI, and the authors

Balconi and Vanutelli (2017), Crivelli et al. (2018) and Balconi and Molteni (2015) speak of its advantage over EEG. As it is non-invasive, fNIRS becomes a good tool for measuring emotional states (Bandaraa *et al.*, 2018), in addition to being able to be used with other monitoring systems, such as pacemakers and hearing aids, as well as being integrated with the EEG, PET and fMRI (Quaresima & Ferrari, 2016). Irani *et al.* (2007) also adds transcranial magnetic stimulation (TMS). In their work on the use of fNIRS in emotions. Balconi and Molteni (2015) conclude that despite the technical limitations, it is a reliable technique to be used in the brain's understanding of emotions and their processing in various contexts, including emotional cues (visual and auditory), social situations or interpersonal interactions

Entering the emotional issue, Venutelli *et al.* (2020) emphasizes that due to the problem of spatial resolution, other neuroimaging techniques can be used "to investigate better the role of cognitive and emotional mechanisms linked to subcortical circuits". Bandaraa *et al.* (2018) is specific when he states that fNIRS cannot reach the amygdala that is directly related to emotions (Bandaraa *et al.*, 2018; Rojiani *et al.*, 2018). These points converge to the fNIRS penetration data discussed by Phillips *et al.* (2020). Balardin *et al.* (2017) also states that "fNIRS is a promising tool for recording brain functional measures in experiments with more ecological validity". For Bosworth *et al.* (2019) the value is in the distinction of different patterns of brain activation, which can help in the development of more intuitive and beneficial interfaces and products to improve the user experience.

fNIRS is a promising, versatile, reliable neuroimaging technique that stands out among other (fMRI, PET, EEG). Can be applied in social context, in clinical experiments, in laboratory environments or in real-life situations, with sensory, cognitive, social and motor stimuli – all these increases the tools flexibility. fNIRS is already used in studies of emotions and can help to understand brain activations in the face of processing the emotions, neurodesign and the affective design, enabling the possible to design better experiences, products, services or environments focused on this affective parameter in front of neurocognition, and promote pleasure and wellbeing.

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