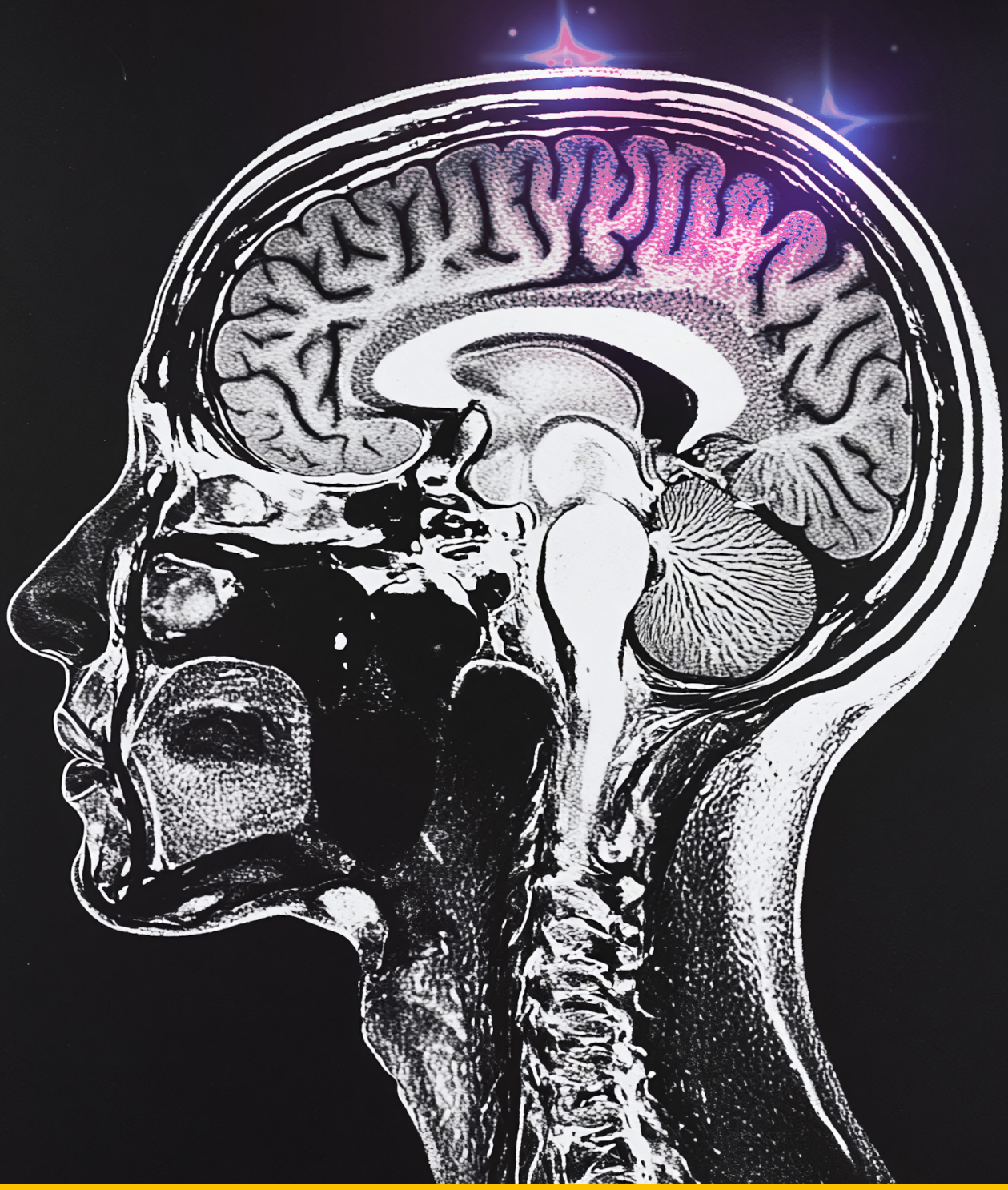
IMOTIONS®

fNIRS Pocket Guide

Near-Infrared Spectroscopy



iMotions - Powering Human Insight

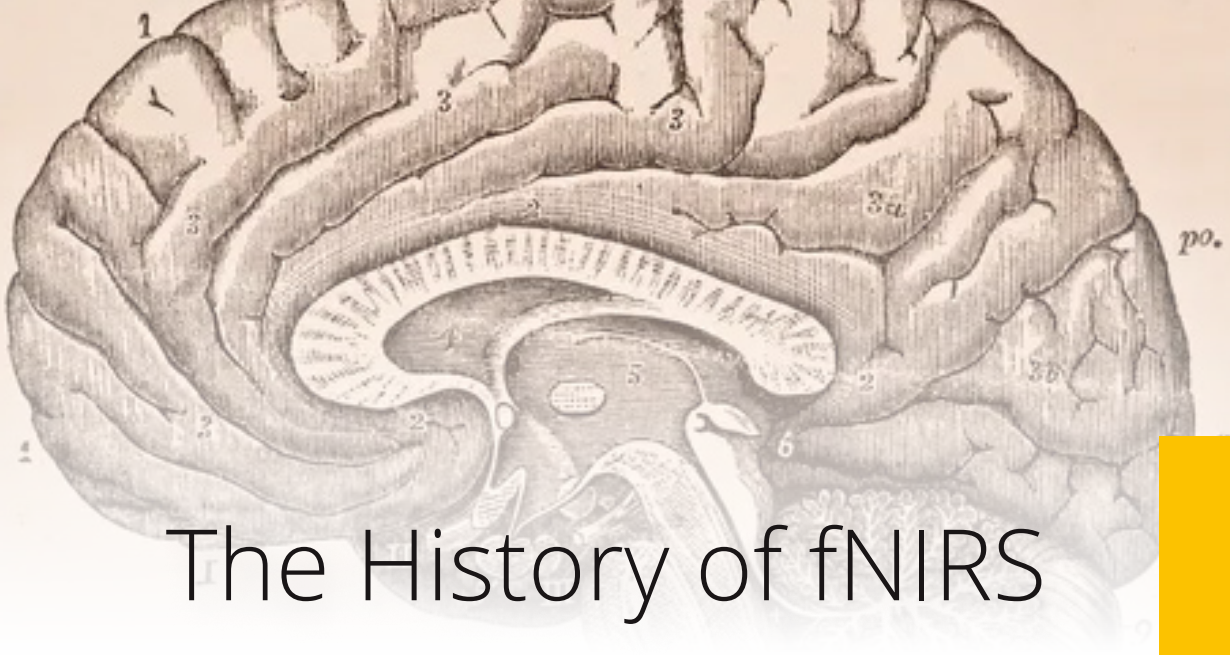
What's inside?

1 Introduction

Welcome to iMotions' pocket guide on functional Near-Infrared Spectroscopy (fNIRS). fNIRS is a powerful and adaptable biosensor offering researchers a non-invasive way to investigate brain functions related to learning, memory, emotional processing, clinical applications, and even brain-computer interfaces. Its portability, resilience to movement, and suitability for participants across all age groups make it an invaluable asset in modern research.

Whether you're just starting with biosensors or are an experienced fNIRS user, this guide provides essential insights tailored to help you make informed decisions. By the end, you'll understand how fNIRS can elevate your research capabilities and be ready to explore its vast potential.

Let's dive in and explore the advantages of fNIRS!



The History of fNIRS

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The development of functional near-infrared spectroscopy (fNIRS) began in 1977, when Frans Jobsis discovered that near-infrared light could penetrate biological tissue, including the brain (*Ferrari and Quaresima, 2012*; *Jobsis, 1977*).

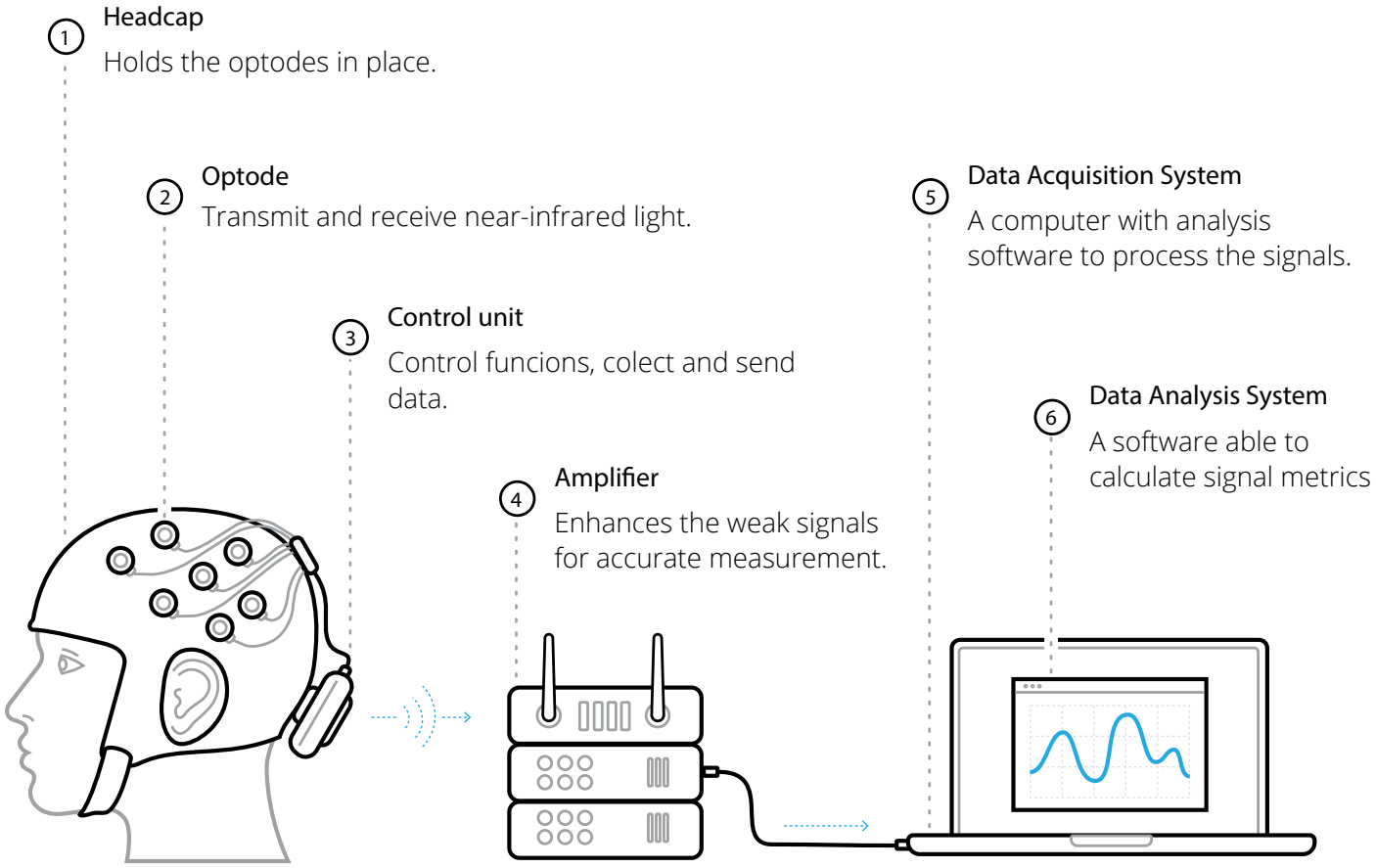
This breakthrough, inspired by oximetry techniques used to measure muscle activity, revealed the potential for near-infrared light to monitor changes in blood oxygen levels—a key indicator of brain activity.

Despite its promising foundation, the technology remained largely experimental for over a decade. It was not until 1993 that the first independent research using fNIRS was published, marking the beginning of its use in neuroscience and clinical studies. From that point on, advancements in hardware and computational methods led to rapid growth in the field, culminating in thousands of scientific publications by the 2020s (*Li et al., 2024*; *von Luhmann et al., 2021*; *Ferrari and Quaresima, 2012*).

Early fNIRS systems were simple, employing a single light source and detector with limited spatial resolution. Over time, innovations introduced dense arrays of channels that could map brain activity in greater detail, rivaling the complexity of electroencephalography (EEG) systems. Modern fNIRS devices now feature higher spatial and temporal resolution, enabling more detailed mapping of brain activity and connectivity.

For an in-depth exploration of the historical progression of fNIRS, Ferrari and Quaresima's 2012 review offers an excellent summary of the technology's evolution from a niche discovery to a widely used neuroscience tool.

3 The fNIRS Setup



A complete fNIRS setup includes a headcap to secure optodes, optodes to transmit and receive near-infrared light, an amplifier to enhance signals, a data acquisition system for signal processing, and a data analysis system for calculating signal metrics. »

The components of the Brite headcap

Key Factors for Placing Optodes

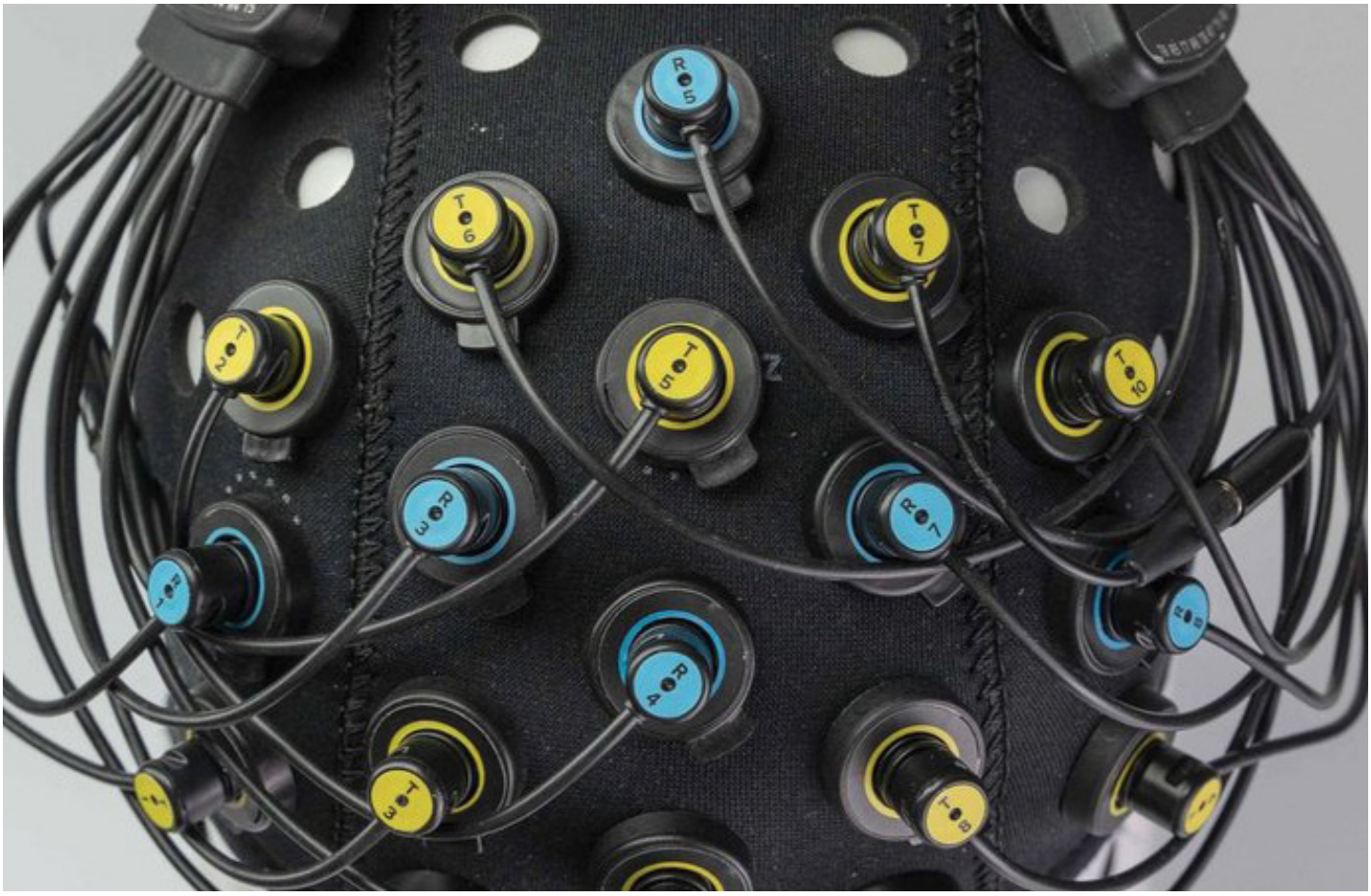
The placement of fNIRS optodes on the scalp determines signal quality. Main considerations are:

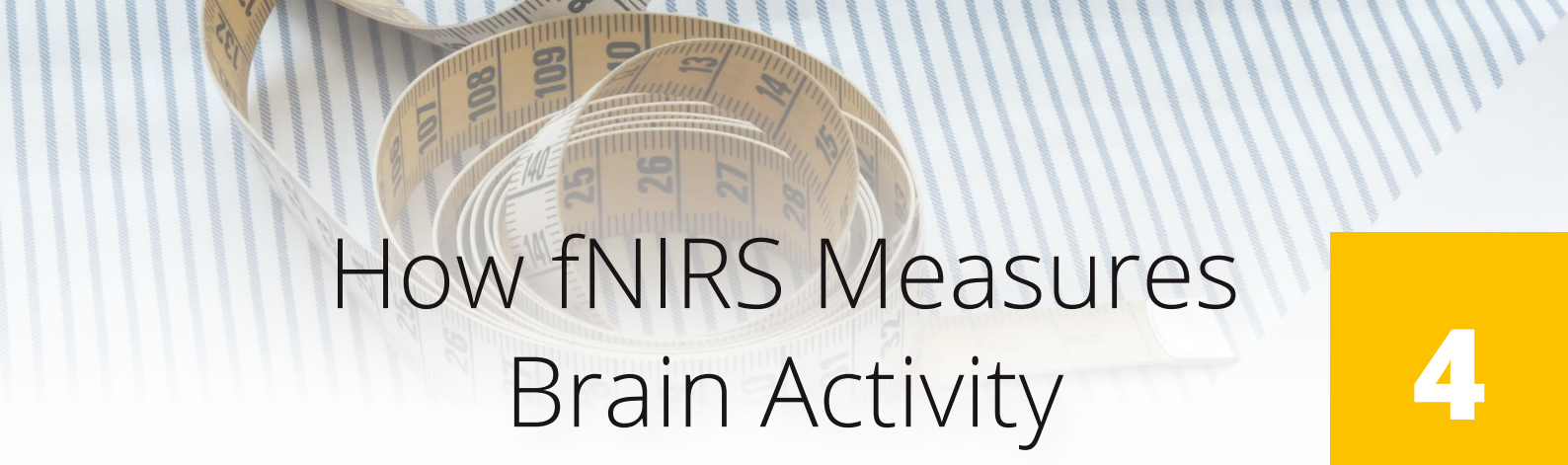
1. **Target Brain Regions**
   The headcap used may allow for optode repositioning to monitor specific brain regions. Using the internationally recognized 10-20 system helps standardize optode placements.

2. Receiver-Transmitter Distance
   For adults, maintain a 25-35 mm distance between the optode's transmitter and receiver, with 30 mm as the standard. For children, this distance varies: about 20 mm for those under 2 years, and 30 mm for older children.

When placing the optodes, it can be helpful to utilize a standardized layout - often referred to as a template or montage - to ensure that each optode - consisting of a transmitter and receiver - are placed at the right distance and the right location.

Despite its technical appearance, setting up and using an fNIRS system is straightforward once you understand each component's role and proper placement techniques.





How fNIRS Measures Brain Activity

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This section includes a deeper introduction to the technical and biological aspects of fNIRS research. While you do not have to be an engineer or mathematician to conduct research with fNIRS, it is helpful to understand the underlying properties of this exciting technology.

The Science Behind the fNIRS Signal

fNIRS measures brain activity by leveraging the distinct light absorption properties of oxygenated (O_2Hb) and deoxygenated hemoglobin (HHb) (*Chen et al., 2020*). Typically, O_2Hb levels rise upon neuronal activity, in contrast, HHb levels rise upon decreases in neuronal activity.

Measuring changes in hemoglobin levels begins with the emission of near-infrared light (~700–900 nm) into the brain through the scalp and skull. This light penetrates the outer layers of tissue and interacts with hemoglobin molecules in the blood, enabling the fNIRS device to measure Total Hemoglobin (tHb) levels and thus estimate total blood flow. Oxygenated hemoglobin (O2Hb) and deoxygenated hemoglobin (HHb) absorb and reflect light differently, allowing fNIRS systems to distinguish between the two.

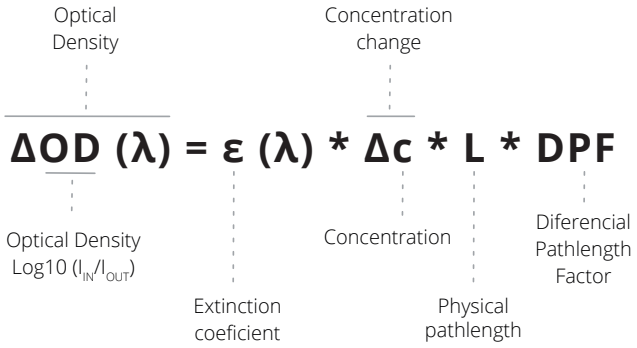
Photodiodes and detectors placed on the scalp capture the light that is reflected back after this interaction. By analyzing the relative absorption and reflection rates of O2Hb and HHb, fNIRS systems can calculate changes in their concentrations over time. These changes correlate with neural activity, as active brain regions require more oxygen, increasing blood flow and shifting the balance of O2Hb and HHb.

This hemodynamic response provides a window into brain function. For example, during a cognitive task, fNIRS can detect an increase in O2Hb and a corresponding decrease in HHb in areas of the brain involved in processing the task. This information, recorded at sampling rates typically ranging from 1–10 Hz (and up to 75 Hz or higher in advanced systems), allows researchers to track brain activity in response to specific stimuli with good spatial and temporal accuracy (*Chen et al., 2020*; *Ferrari and Quaresima, 2012*).

Through this mechanism, fNIRS offers a non-invasive way to study neural processes, bridging the gap between electrical and hemodynamic measures of brain function.

Calculating the Hemodynamic Response with fNIRS

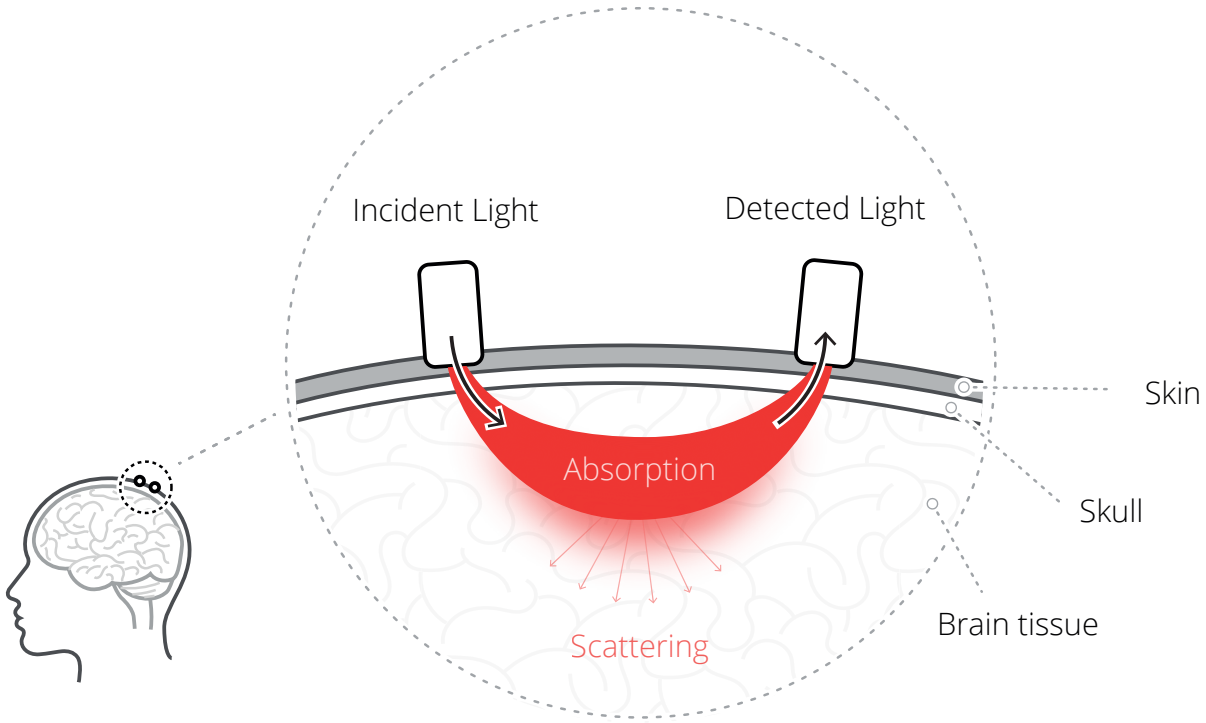
The fNIRS signal relies on complex calculations to interpret changes in light absorption accurately. Researchers use open source toolboxes such as Homer, NIRS-Toolbox, and MNE-Python when analyzing fNIRS data to align with scientific standards.



Llambert-beer equation:
from Optical Density to Concentration change

Under perfect circumstances, 100% of the near infrared light emitted would enter the brain tissue. However, the skull, skin, and brain tissue itself lead to light scattering and absorption. In other words, when we calculate O2Hb and HHb, we are doing it based on the attenuated signal that makes it to the hemoglobins. Using the Modified Lambert-Beer Law, researchers calculate hemoglobin concentration changes based on the attenuated light that reaches brain tissue (*Scholkmann and Wolf, 2013*).

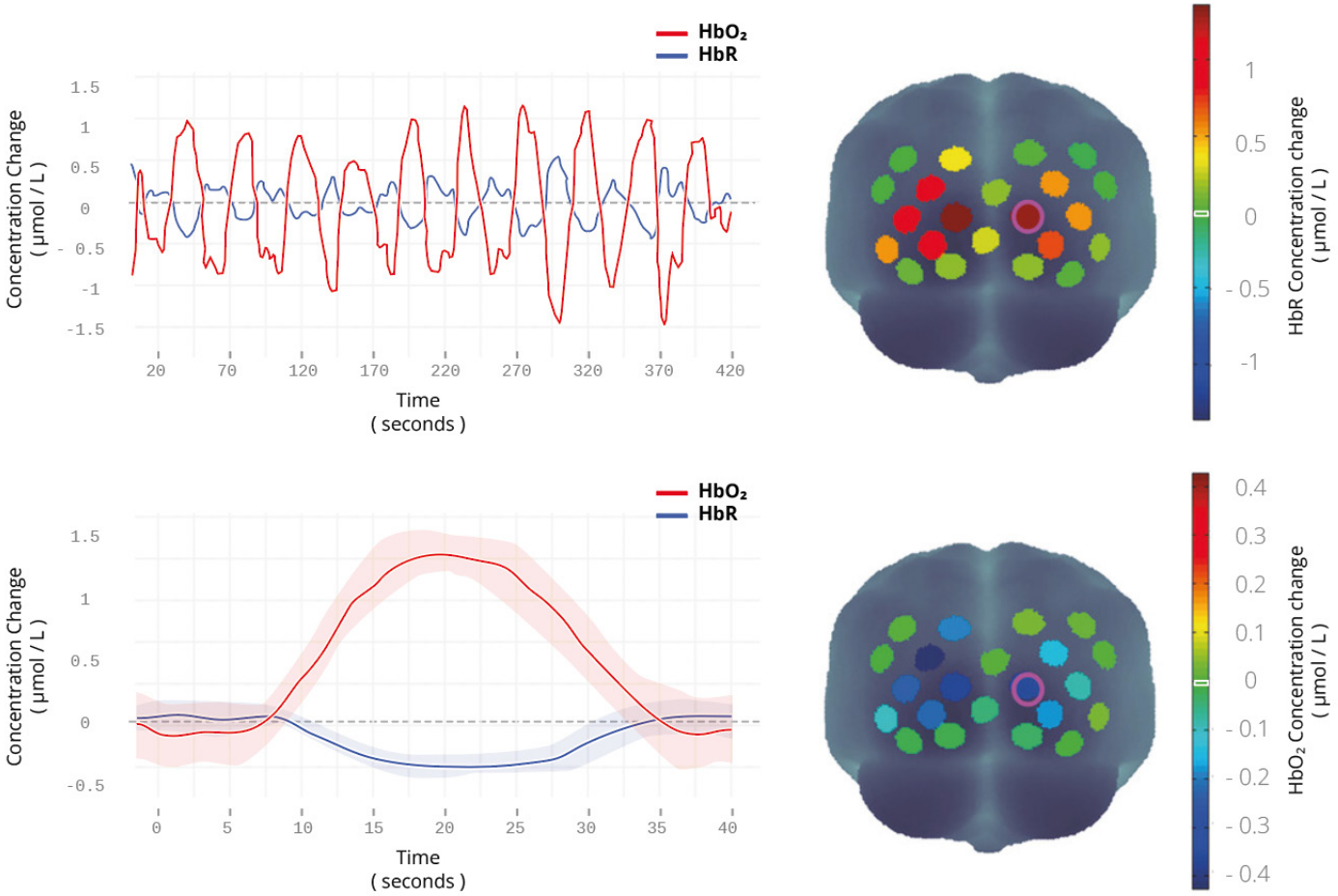
Within this equation, the Differential Pathlength Factor (DPF), a unitless scaling factor that estimates how far light travels through a certain tissue, accounts for the scattering and attenuation of the near infrared light emitted into the scalp by the laser diodes. The DPF is typically kept constant, but its value varies depending on the type and age of the tissue (*Scholkmann and Wolf, 2013*). Typically, brain tissue has a DPF of 6, and muscle tissue has a DPF of 4. We encourage the interested reader to explore more details about the hemodynamic response in scientific literature (*Scholkmann et al., 2014*).



The Hemodynamic Delay

The hemodynamic response is slower than neuronal activity, with about a 5-second delay for signal onset following a stimulus and around 16 seconds for signal normalization post-stimulus (*Pinti et al., 2018*).

Researchers must consider this delay when interpreting fNIRS data, aligning brain activity changes with behaviors occurring roughly 5 seconds prior. Open Source tool boxes such as Homer, FieldTrip, and MNE-Python adjust for this delay.



5 fNIRS Research Applications

From clinics to consumer labs, fNIRS has become a more accessible tool for researchers exploring brain activity in real-world settings. The following section showcases some of the most common and impactful ways fNIRS is being used today.

Cognitive Neuroscience

fNIRS is a popular method to study cognitive states and functions, and being more affordable and portable, it is commonly substituted for EEG or other advanced imaging options. For example, *Agbanla et al., (2022)* reported a correlation between hemodynamic activity in distinct areas of the prefrontal cortex (PFC) with behavioral performance on two executive function tasks.

Cognitive function changes with age, and researchers have used fNIRS to identify how brain activity contributes to this age-related decline. *Ranchod et al. (2023)* found that, compared to younger adults, older individuals (age 64-84) show greater bilateral PFC recruitment during cognitive tasks - supporting the hypothesis that older adults engage compensatory brain regions to maintain cognitive performance. The following year, the same group added nuance to these findings by showing that older adults exhibit distinct relationships between hemodynamic brain activity and reaction time during cognitive tasks (*Gonzalez et al., 2024*). These results underscore the value of fNIRS in illuminating typical aging processes and point to its potential in clinical research.

fNIRS is also used for pre- and post-assessments to understand treatment impact on cognitive function. One randomized controlled trial found consistent improvements in cognitive function, including increased PFC activation upon daily ingestion of a polyphenolic-rich supplement (*Best et al, 2024*).

Infant and Childhood Brain development

Due to the thinner skulls and (often) light density of hair, fNIRS has a long history of being used in infant research (*Vanderwert and Nelson, 2014*), and the non-invasive, portable, and high movement tolerance nature of fNIRS has made it a mainstay in infant research. Researchers use fNIRS to study cognitive and motor development in infants, including memory, language, and facial recognition

(*Wang et al., 2019*; *Wilcox and Biondi, 2015*).
fNIRS is also frequently employed in low-resource settings for studies on cognitive function and nutrition's impact on infant brain health, such as assessing working memory in rural African infants (*Begus et al., 2016*; *Lloyd-Fox et al., 2014*), with implications for our understanding of how (mal)nutrition affects brain development and function (*Galler et al., 2021*).

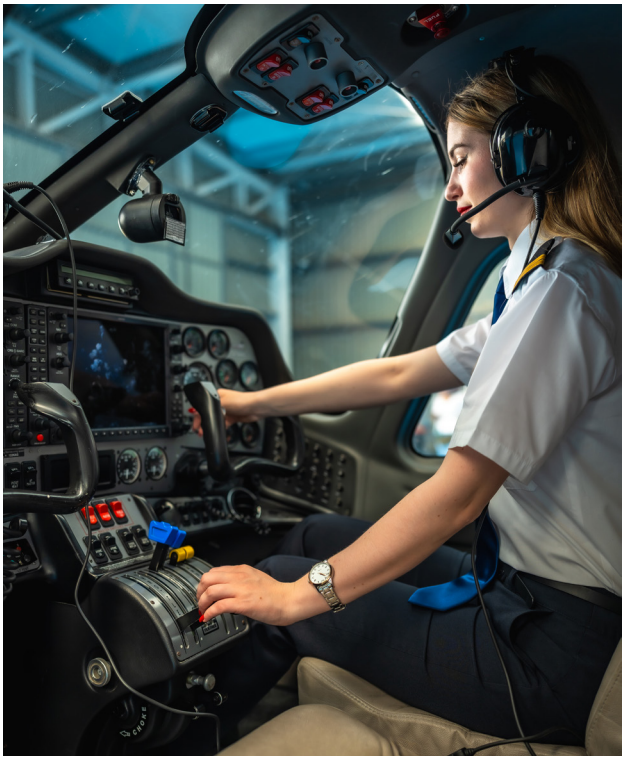
Increasingly, fNIRS is used to identify neural markers of neurodevelopmental disorders like autism spectrum disorders (ASDs) (*Scaffei et al., 2023*; *Conti et al., 2022*; *Mazziotti et al., 2022*). This emerging field shows promise for early detection and intervention by identifying unique brain activity patterns associated with neurodevelopmental disorders. Notably, fNIRS's reduced sensitivity to movement is beneficial in infant research, allowing for continuous monitoring even with frequent movements.

Social Interactions

Human interactions are integral to our cognitive and emotional development, and fNIRS has helped illuminate how social experiences shape the brain. Research has captured brain responses to affective touch and identified abnormalities linked to social skills challenges (*Bennett et al., 2013*).
A growing area of interest is inter-brain synchronization — the phenomenon of shared brainwave patterns among individuals. For example, studies have evaluated what happens in the brains of people when they touch each other (*Zhao et al., 2024*), while others have studied how inter-brain synchronicity is influenced by working in competitive vs cooperative teams (*Lu et al., 2018*).

Human Factors & Performance

fNIRS has transformed the study of human factors by enabling cognitive workload assessment in real-world settings outside laboratory constraints. One study compared pilots' cognitive workload in simulators and actual aircraft, finding that frontal cortex activity and error rates were higher during real flights, highlighting the unique cognitive demands of real-world tasks (*Gateau et al., 2018*). Another study used fNIRS and eye-tracking to distinguish cognitive and attentional patterns between expert and novice operators facing unexpected challenges. Experts displayed higher activity in the dorsolateral prefrontal cortex and longer visual fixation, suggesting an adaptive response to problem-solving (*Isbilir et al., 2019*).



Clinical & Rehabilitation

Understanding and treating clinical conditions is a critical area of research, and fNIRS has emerged as a valuable tool in both diagnosis and treatment monitoring. It has been used to detect conditions, such as Parkinson's Disease (PD) and Major Depressive Disorder (MDD), as well as to support treatment development for complex illnesses like PD and Myofascial Pain Syndrome (MPS) (*Beretta et al., 2024*; *Guevara et al., 2024*; *Du et al., 2023*; *Yi et al, 2023*; *Orcioli-Silva et al., 2021*).

MDD is one of the most common mental health disorders, yet it often goes undiagnosed. *Yi et al. (2023)* combined EEG and fNIRS to examine differences in brain oxygenation and delta and theta band activity between depressed and non-depressed individuals. Using machine learning, their model achieved 92.7% classification accuracy - highlighting the potential for fNIRS-based approaches to enable faster and more accurate diagnoses.

In a randomized controlled trial, *Beretta et al. (2024)* examined brain changes associated with Transcranial direct current stimulation (tDCS) of the motor cortex in PD patients. By comparing pre- and post-intervention PFC hemoglobin activity, they found reduced brain activation that correlated with improved neuromuscular and postural response, supporting the idea that tDCS may enhance motor function in PD through modulation of brain activity.

For individuals with MPS, a chronic pain condition with limited treatment options, *Du et al. (2023)* investigated the impact of wrist- and ankle-based Transcutaneous Electrical Nerve Stimulation (TENS) on pain-related brain activity. Post-intervention fNIRS data revealed significant reductions in hemoglobin levels in PFC regions typically involved with pain processing, suggesting that this non-invasive approach could offer a promising avenue for managing chronic pain in MPS patients.

fNIRS & Virtual Reality

Virtual Reality (VR) combined with functional near-infrared spectroscopy (fNIRS) is revolutionizing behavioral research by providing deeper insights into brain processes during complex behaviors. This pairing has advanced understanding in areas like preschoolers' social development, racial biases, industrial maintenance, and neurorehabilitation(*Bulgarelli et al., 2023*; *Shi et al, 2020*; *Kim et al., 2019; Holper et al., 2010*).

fNIRS's resistance to motion makes it ideal for VR research, where movement is often encouraged. For example, a study on manufacturing workers in high-stress VR tasks linked brain activity, performance, and visual attention (*Shi et al, 2020*), offering strategies to enhance workplace efficiency and safety. Similarly, research on preschoolers interacting with avatars in VR identified brain networks tied to social preferences, shedding light on early social brain development (*Bulgarelli et al., 2023*).

Exercise Science

fNIRS is particularly popular in exercise science, where researchers use it to examine the effects of physical activity on brain function (*Shen et al., 2024*). Studies in this area typically fall into three categories:

1. **Effects of Regular Exercise on Brain Health**
   Researchers explore how consistent exercise regimens impact cognitive and neurological function over time.
2. Immediate Impact of Acute Exercise
   These studies assess brain function changes immediately following a single exercise session.
3. Brain Activity During Exercise
   This group focuses on brain function as it occurs during physical activity, with tasks like cycling, walking, or running, which avoid rapid head movement to minimize motion artifacts (*Shen et al., 2024*).

For studies examining cognitive effects of exercise, fNIRS often measures brain activity in the prefrontal cortex during tasks such as the Stroop, N-back, and Flanker tasks. Findings generally show enhanced cognitive function and increased O2Hb in the prefrontal areas post-exercise, indicating improved brain function (*Shen et al., 2024*). For example, mild cycling for 10 minutes has been associated with better Stroop task performance and higher O2Hb in key prefrontal areas (*Shen et al., 2024*).

Real-Life Activities

fNIRS's portability, wireless design, and resilience to minor motion artifacts make it ideal for studying brain activity during real-life tasks. Studies have successfully applied fNIRS to diverse activities, including music practice, table tennis, and daily routines (*Pinti et al., 2018*; *Balardin et al., 2017*; *Pinti et al., 2015*).

Although real-life tasks introduce potential artifacts (e.g., sunlight or motion), fNIRS remains effective where other brain sensors struggle, providing insights into brain activity in authentic, naturalistic environments (*Pinti et al., 2018*).

Marketing, Usability, and Decision Making

Biosensor tools, including fNIRS, are increasingly being used to explore how people perceive brands, navigate websites, and make financial decisions. These tools provide

objective, quantifiable insights that augment traditional self-reported data.

fNIRS has revealed distinct brain activity patterns during purchase decisions involving favorite versus non-favorite brands (*Krampe et al., 2018*), assessed mental workload on car insurance websites (*Lukanov et al., 2016*), and evaluated website design likeability (*Nissen et al., 2024*). It has also played a significant role in neuroeconomics, aiding research on financial decision-making in both academic and consumer contexts (*Kopton and Kenning, 2014*).

This growing application of fNIRS highlights its value in understanding consumer behavior and improving user-centered design.

Multimodality

Researchers often rely on a multimodal approach to better understand human behavior, emotions, and cognition. fNIRS is well-suited for integration with other biosensors and AI-driven technologies, including eye-tracking, galvanic skin response (also known as electrodermal activity), and voice analysis. However, among these, the most common pairing is with EEG (e.g. Naik et al., 2024; *Zakeri et al., 2023*; *Yi et al., 2023*; *Orcioli-Silva et al., 2021*; *Rezzaee et al., 2021*).

For instance, *Zakeri et al. (2023)* combined EEG and fNIRS to understand the cognitive impact of working alongside collaborative robots (cobots) in factory settings.

By simultaneously capturing electrical brain activity and hemoglobin responses, the researchers were able to detect real-time moments of physiological stress and cognitive overload, which correlated with behavioral and subjective measures.

fNIRS may also be paired with electromyography (EMG) and electrocardiography (ECG). In one study, *Naik et al. (2024)* integrated fNIRS, EMG, ECG, EEG, and eye tracking to assess cognitive workload in surgical trainees. Using this multimodal data, the team developed a highly accurate model to identify moments of elevated cognitive demand, creating opportunities for real-time interventions and performance optimizations.

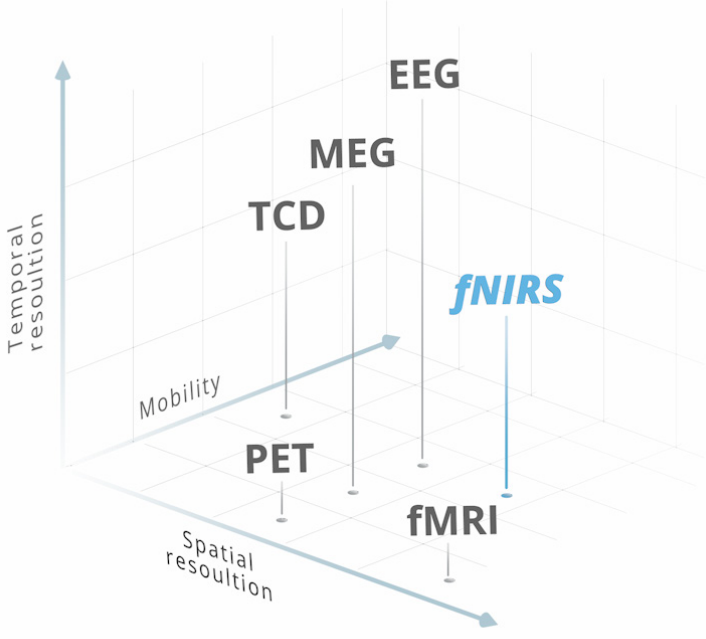
In summary

fNIRS has opened new doors for studying the brain in diverse settings — from controlled laboratory tasks to the unpredictability of real-life situations. Its portability, ease of use, and resilience to motion artifacts make it invaluable for examining cognitive, social, and developmental processes in contexts where other brain-monitoring tools may fall short. Through fNIRS, researchers gain a clearer understanding of the neurobiological foundations of cognitive functions, providing a bridge between laboratory findings, clinical research, and real-world applications.

fNIRS in Multimodal Biosensor Research

6

fNIRS has become an indispensable tool in neuroscience and behavioral research by filling key gaps in brain activity measurement technologies. In this section, we'll examine how fNIRS compares to other leading methods like EEG and fMRI, how it can complement various sensors, and the unique advantages that make it valuable in today's research landscape.



Comparing fNIRS to other brain activity sensor technologies

Graph: *Comparing diffrent brain activity sensor technologies on 3 axies : Temoral resoultion, Spatial resolution and Degree of moblility .*

fMRI and fNIRS

fMRI and fNIRS both measure brain activity through correlational changes in cerebral blood flow (neurovascular coupling), yet they differ significantly in approach and use. (*Chen et al., 2020*). fNIRS uses near-infrared light to detect levels of oxygenated and deoxygenated hemoglobins in blood, providing information on brain activity. By contrast, fMRI measures blood flow using the BOLD (blood oxygen level-dependent) signal, based on magnetic changes in hemoglobin.

In terms of setup, fNIRS is compact, portable, and involves a simple cap with photodiodes and detectors (*Chen et al., 2020*; *Scarapicchia et al., 2017*). fMRI, however, requires a large, stationary MRI scanner, which restricts participant eligibility, especially for those with metal implants and claustrophobia. fNIRS allows for more natural movements, making it ideal for studies involving motion. Though fMRI offers greater depth and spatial resolution, fNIRS provides a practical, cost-effective alternative with reasonable spatial accuracy, especially for cortical measurements. A notable advantage of fNIRS is its higher tolerance to natural movement, and the device

is therefore often used in studies where participants bike, run or engage in other movement activities (*Pinti et al., 2018*).

EEG and fNIRS

EEG (electroencephalography), a widely used technology, measures electrical activity in the brain. Unlike fNIRS and fMRI, which rely on slower hemodynamic responses, EEG provides millisecond-scale temporal resolution, allowing precise tracking of signal timing. However, EEG has limited spatial accuracy due to signal spread across the scalp.

EEG and fNIRS are complementary, with some researchers now combining them to capture both the "where" (fNIRS) and "when" (EEG) of brain activity (see for example *Su et al., 2023* and *Li et al., 2022*). While the EEG setup can be more cumbersome, recent innovations have improved portability. Both EEG and fNIRS are relatively affordable, though fNIRS is generally less sensitive to movement artifacts (*Checklman et al., 2010*).

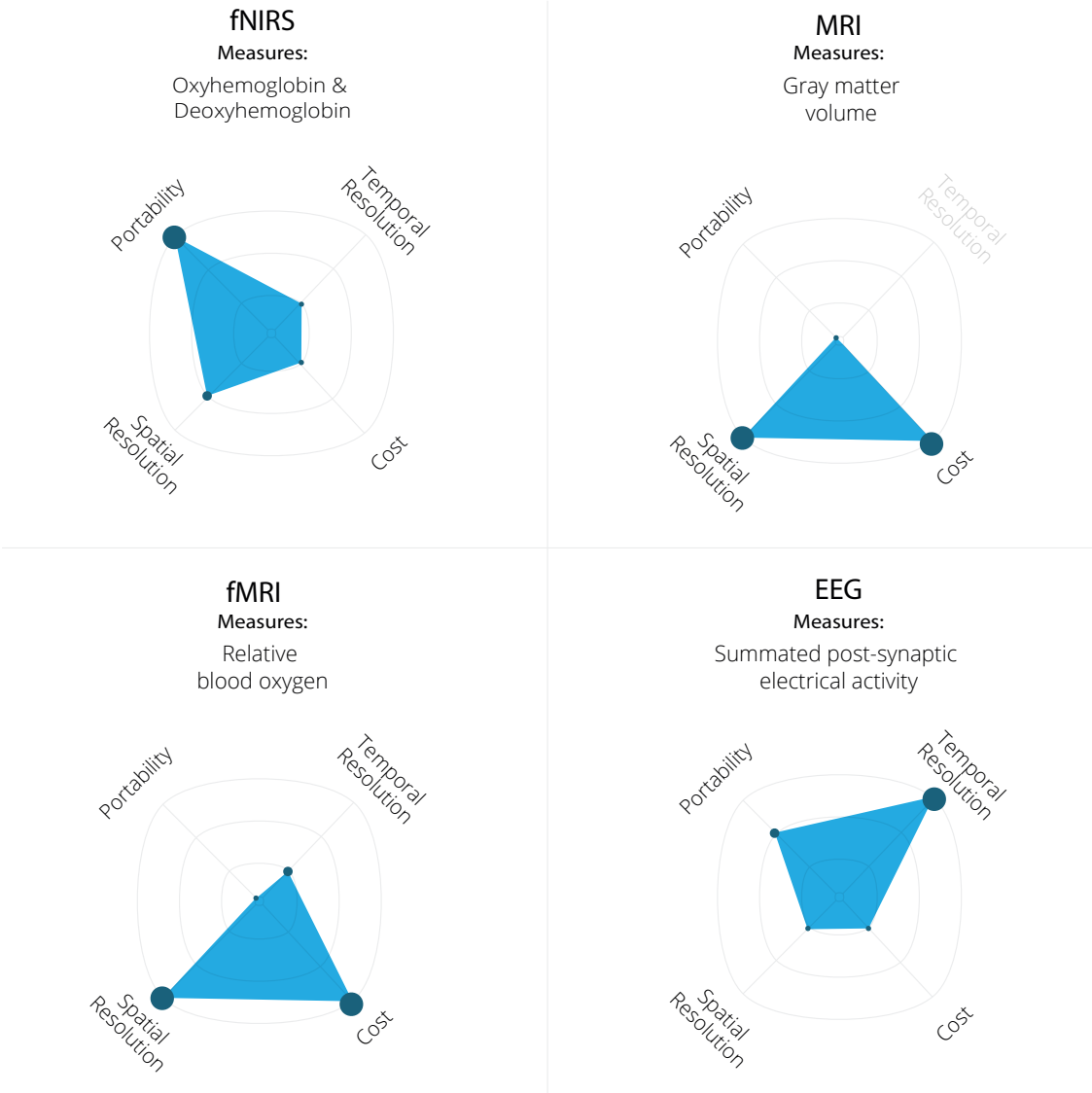


Table:
Comparison of four brain activity measurement technologies based on: portability, temporal resolution, spatial resolution, and cost.

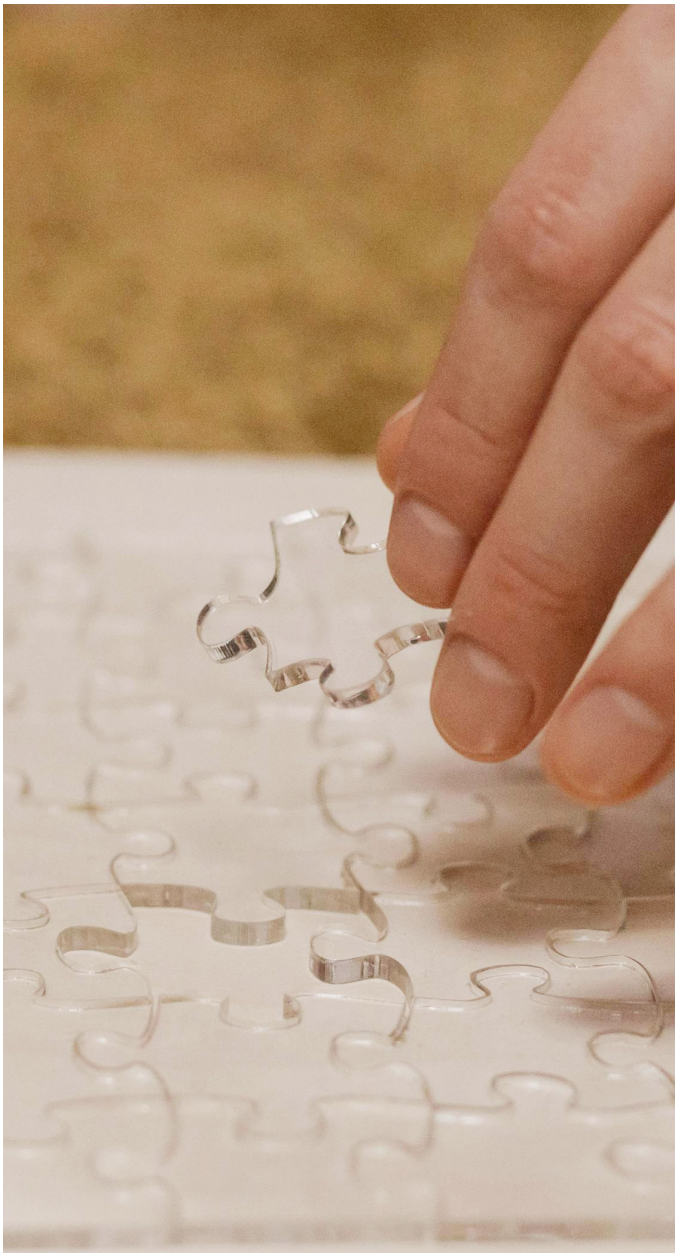
Choosing between EEG and fNIRS often depends on research goals: EEG is optimal for tracking the timing of neural events, while fNIRS is ideal for pinpointing spatial location. For those needing both insights, combined EEG-fNIRS systems offer a powerful solution.

How fNIRS complements other technologies

Combining fNIRS with other sensors provides a richer view of human cognition and behavior by capturing multiple physiological signals (*von Luhmann et al., 2021*):

- **Gaining a Holistic Understanding:** No single sensor can capture the full range of human experience. Pairing fNIRS with EEG, for instance, allows researchers to capture both spatial and temporal data, enhancing the study of brain activity dynamics.
- **Minimizing Artifacts:** Although fNIRS is less artifact-prone than some other methods, motion and physiological interference can still impact data quality. Combining fNIRS with sensors like accelerometers and cameras helps to reduce these errors by cross-referencing movement and environmental factors.
- **Linking Brain Activity to Behavior:** fNIRS pairs well with technologies like eye tracking, electromyography (EMG), and galvanic skin response (GSR) for studying how physiological responses relate to specific actions, emotions, or thoughts (*Daniel et al., 2023*; *Wang et al., 2023*; *da Silva Soares et al., 2022*; *Isbilir et al., 2019*; *Katus et al., 2019*; *Murphy and Holper, 2014*). For instance, eye tracking helps identify focus areas, while EMG can reveal motor patterns, adding depth to brain activity analyses.

When using multiple sensors, precise synchronization is crucial, as fNIRS's hemodynamic signals have a 5–10 second



delay relative to stimuli. Proper alignment ensures that different signals contribute accurately to a comprehensive analysis.

Choosing the right data collection software is a critical step in overcoming this challenge and taking advantage of the opportunities of multimodal research.

Unique advantages of fNIRS

By now, it should be clear that the fNIRS system holds a highly relevant place in behavioral research. Here we summarize the unique advantages and disadvantages of fNIRS.

Advantage of fNIRS	**Disadvantage of fNIRS**
Noninvasive	Limited spatial depth
Good spatial resolution	Low temporal resolution
Portable	5-10 second response delay
Less movement sensitive	
User-friendly setup	
Cost-effective	
Easily integrated with other sensors	
High safety	

7 Analyzing and understanding fNIRS data

With a clear understanding of fNIRS technology and its applications, the next step is to explore how to process and interpret the signals it captures. This section outlines the key metrics used in fNIRS research, how to ensure signal quality, and the critical preprocessing steps required to extract meaningful insights.

Key Metrics in fNIRS Research

The key metrics in fNIRS research focus on the hemodynamic changes in the brain, specifically involving oxygenation and blood flow. These metrics include:

1. **Oxygenated Hemoglobin (O2Hb)**
   - **What It Is:** The concentration of hemoglobin bound to oxygen.
   - **What It Indicates:** O2Hb increases in areas of heightened brain activity, reflecting an influx of oxygenated blood during neural activation.
   - **Importance:** O2Hb is the most commonly analyzed metric in fNIRS studies due to its strong correlation with brain activation.
2. **Deoxygenated Hemoglobin (HHb)**
   - **What It Is:** The concentration of hemoglobin that has released its oxygen to the brain tissue.
   - **What It Indicates:** HHb typically decreases in regions of brain activity as oxygen is consumed and replaced by fresh, oxygenated blood.
   - **Importance:** HHb provides complementary information to O2Hb, offering a more complete picture of neural activity.
3. **Total Hemoglobin (HbT)**
   - **What It Is:** The combined concentration of O2Hb and HHb.
   - **What It Indicates:** HbT reflects total blood volume changes in the brain, which can signify vascular activity.
   - **Importance:** HbT is useful for understanding changes in cerebral blood flow and overall vascular dynamics.

The changes measured by fNIRS result from two key processes *(Pinti et al., 2021)*:

1. **Neurovascular coupling**
   When brain cells are active, they need more oxygen and nutrients. To meet this demand, nearby blood vessels dilate, increasing blood flow to the area. This delivers more oxygenated hemoglobin and reduces deoxygenated hemoglobin, which is what fNIRS detects.
2. **Neurometabolic activity**
   Active neurons use glucose and oxygen to produce energy. As oxygen is consumed, the blood flow increase compensates by delivering fresh oxygen and removing waste products like carbon dioxide.

During increased activity in a brain region, neurovascular and neurometabolic processes occur simultaneously. Neuronal activity increases oxygen demand, briefly reducing local O2Hb levels. However, neurovascular coupling causes blood vessels to dilate, rapidly delivering more oxygenated hemoglobin (O2Hb) to the area. This oversupply outweighs oxygen consumption, resulting in a net increase in O2Hb despite the heightened metabolic demand.

Some advanced analyses derive additional metrics from these primary measures (*Herold et al., 2018*)

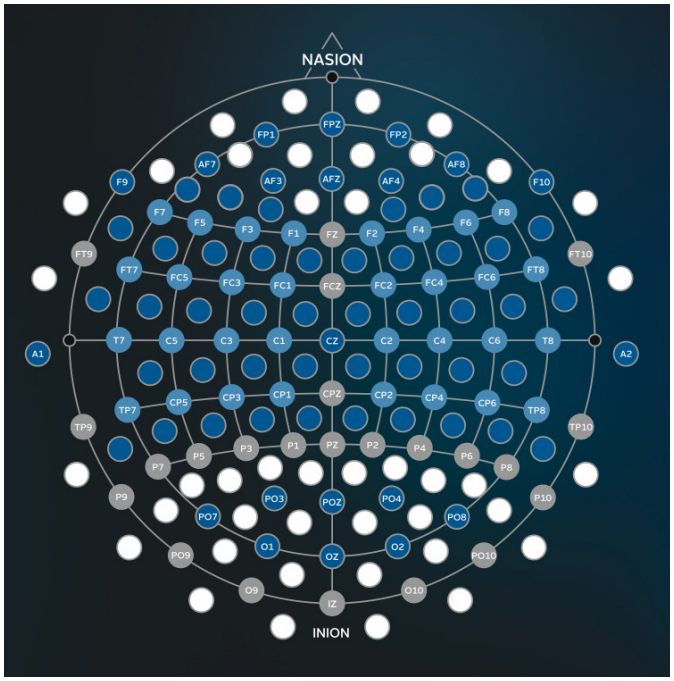
- **Oxygenation Index (OI):** The ratio or difference between O2Hb and HHb, providing a single-value representation of oxygenation levels.
- **Functional Connectivity:** Correlations between O2Hb or HHb signals in different brain regions, often used in resting-state studies.

These metrics collectively enable researchers to study brain function, connectivity, and responses to cognitive, emotional, or physical stimuli with a high degree of spatial accuracy.

Evaluating the fNIRS Signal

Ensuring good signal quality before data recording is critical for reliable results. Here's what to evaluate:

1. **Stable Baseline**
   A stable baseline signal during rest is essential. Drift or instability may indicate poor contact between the cap and scalp, often caused by hair or air gaps. Adjust optodes to achieve consistent readings.



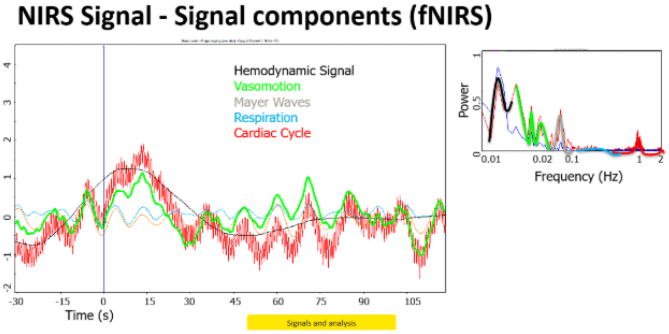
2. **Consistency Across Channels**
   Uniformity in signal quality across all channels suggests proper cap placement. If specific channels show issues, check the optodes or recorders for alignment problems.

3. **Minimal Motion Artifacts**
   Although fNIRS is relatively robust against minor movements, rapid head turns or facial expressions can introduce artifacts. Secure the optodes and minimize participant movement to ensure clean signals.

4. **Adequate Penetration Depth**
   The distance between the light source and detector (2.5–3.5 cm) is critical for reaching cortical tissue. Distances that are too short measure only superficial layers, while those too long may degrade signal quality.

5. **Clear Hemodynamic Response**
   The signal should reflect task-related changes, with increases in O2Hb and decreases in HHb during activity. Physiological noise (e.g., respiration, cardiac rhythms) may appear but should not dominate the signal.

6. **High Signal-to-Noise Ratio (SNR)**
   Ensure a clear distinction between task-related signals and background noise. If the SNR is low, revisit the previous steps to address potential causes.



Several studies provide further guidance on identifying noise and ensuring high signal quality (*Scholkmann et al., 2022*; *Pinti et al., 2019*; *Isbilir et al., 2019*; *Hocke et al., 2018*). It becomes easier to understand the multi fold nature of the fNIRS signal, once we separate the signals using bandpass filtering. This breakdown helps filter and analyze the fNIRS signal by separating physiological noise from the target hemodynamic response.

Signal	Frequency range (Hz)
Hemodynamic Signal (VLF and LF Oscillations)	>0.2
Vasomotion	~0.1
Respiration	~0.2 - 0.5
Cardiac Cycle	~1 - 1.5

Pre-Processing of the fNIRS signal

Data preprocessing is crucial for reliable results. Using recognized Open Source tools like Homer, NIRS-Toolbox, or MNE-Python ensures processing meets scientific standards. Here are key steps for processing fNIRS data.

1. **Data Quality Check**
   Inspect raw signals for motion artifacts, optode disconnections, or baseline drift. Address any issues to ensure clean data input.

2. **Conversion to Optical Density (OD)**
   Raw intensity values are converted to OD to account for ambient factors and prepare for hemoglobin concentration analysis. This step standardizes the data.

3. **Motion Artifact Correction**
   Use techniques like wavelet filtering to minimize the impact of participant movement. While there is no universal method, wavelet filtering is commonly employed.
4. **Bandpass Filtering**
   Apply filters to isolate the hemodynamic signal. Typical ranges are:
   - **Low-pass:** Removes high-frequency noise (e.g., cardiac signals) above ~0.1 Hz.
   - **High-pass:** Removes low-frequency drift below ~0.01 Hz.

Note that the exact ranges vary and are highly dependent on the research question.

5. **Conversion to Hemoglobin Concentrations**
   Using the modified Beer-Lambert Law (MBLL), OD data is transformed into O2Hb and HHb concentrations. This step directly links signal changes to brain activity.
6. **Baseline Correction**
   Normalize data by subtracting a pre-task baseline mean, reducing inter-subject variability and improving comparability.
7. **Data Segmentation**
   Divide the signal into epochs aligned with task timing. Remove epochs with significant artifacts to ensure clean segments for analysis.
8. **Smoothing**
   Apply a moving average or Gaussian filter to enhance signal clarity and reduce noise.
9. **Final Quality Check and Export**
   Perform a visual inspection of the preprocessed signal to confirm artifact removal. Export the cleaned data for further analysis.

Completing these preprocessing steps ensures your data meets high-quality standards, as required by most peer-reviewed journals. For further information on processing methods, refer to : *Yucel et al., 2021*, *Klein and Krancziоc, 2019*, *Pinti et al., 2019*, *Pinti et al., 2018*, *Hocke et al., 2018*, *Friston et al., 1994*.

Processing requirements may vary for different populations (e.g., children or clinical populations) and research goals, so it is essential to understand the needs specific to your participant group. »

Summary & Key Takeaways

Effective fNIRS analysis begins with ensuring signal quality — stable baseline, minimal motion artifacts, proper optode placement, and high signal-to-noise ratio.

Key preprocessing steps include artifact correction, filtering, and converting to hemoglobin concentrations (O2Hb and HHb), which reflect brain activity. Tailoring preprocessing to specific participant groups, like children, may further enhance data quality.

These steps enable reliable insights into brain function and cognitive processes.

Key Considerations for Using fNIRS in Research

8

When integrating fNIRS into your research, it's essential to account for factors such as experimental design, technical limitations, and potential sources of error. This guide provides an overview of key considerations to help ensure accurate and reliable results.

1. Include a Baseline Period

The fNIRS signals (O_2Hb, HHb, and tHb) are relative, requiring a well-defined baseline period before the experimental intervention. The baseline setup should closely match the intervention conditions to minimize variability. Inspect the baseline for artifacts like motion or noise that could distort results. void comparing baseline averages between groups, as fNIRS measures are relative and subject to individual anatomical differences. To ensure consistency, do not remove the sensor between the baseline and intervention periods.

2. Experimental Design: Selecting the Right Study Design

The success of your fNIRS study begins with choosing the right design, which depends on your research question and goals. Common study designs include:

- **Block Design**
  Alternates between task and rest periods to capture sustained neural activity. This approach is reliable and easy to implement but may introduce habituation (reduced response over time) and anticipation effects (participants predicting stimuli).

  Moreover, it is not possible to isolate responses to individual stimuli.

- **Event-Related Design**
  Measures responses to brief stimuli, making it ideal for studying rapid cognitive processes. In contrast to the Block Design, Event-Related Designs can isolate responses to individual stimuli. While it allows fine-grained temporal resolution, the signals can be weaker compared to block designs.

- **Resting-State Design**
  Captures intrinsic brain connectivity without external stimuli. It's particularly useful for exploring large-scale brain networks and default-mode activity.

- **Pre-Post Intervention Design**
  Measures the effect of a training period on the brain or muscle's function. Such a design is often used in cognitive neuroscience and sports science.

Select a design that aligns with your research goals, considering which cognitive processes or brain regions you aim to study.

3. fNIRS Setup: Probed vs. Whole-Brain

The choice of an fNIRS setup depends on whether your study focuses on specific brain areas or broad connectivity.

- **Probed Setup**
  Targets specific brain regions with high spatial resolution, offering simplicity and lower costs. However, it limits the scope of analysis to predefined areas.

- **Whole-Brain Setup**
  Covers the entire scalp, allowing for comprehensive mapping of brain activity and connectivity. While this approach is versatile, it's more expensive and requires complex data processing.

Consider the trade-offs between focus and comprehensiveness when selecting your setup.

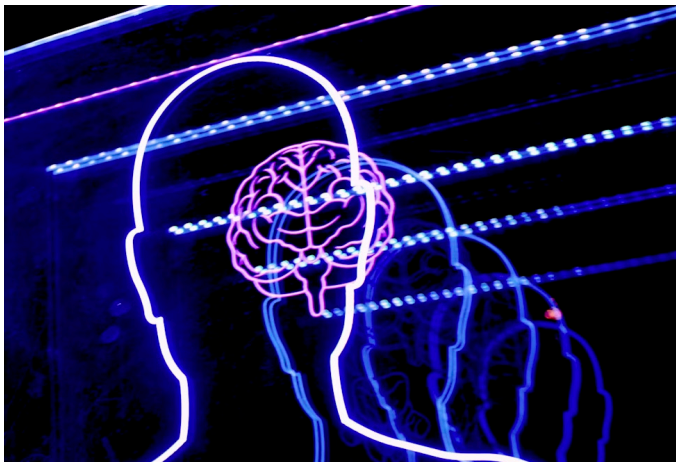
4. Technical Limitations

While fNIRS is a powerful tool, it comes with inherent limitations researchers must address:

- **Hemodynamic Delay**
  Neural activity causes a blood oxygenation response with a delay of 2–6 seconds. When analyzing event-related designs or precise timing, account for this lag to avoid misattributing neural activity to incorrect stimuli.

- **Limited Spatial Depth**
  fNIRS can only measure activity within 1–3 cm of the scalp, making it ideal for cortical studies but unsuitable for investigating deeper brain structures.

- **Synchronization**
  For studies involving multiple data sources (e.g., EEG, GSR, or behavioral metrics), synchronization is critical. Specialized equipment and software ensure accurate timing across modalities, reducing the risk of errors in interpreting cross-modal relationships.



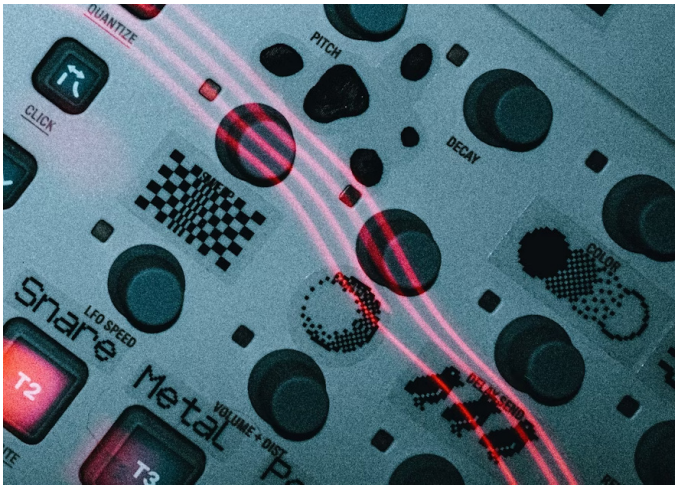
5. Potential Sources of Error

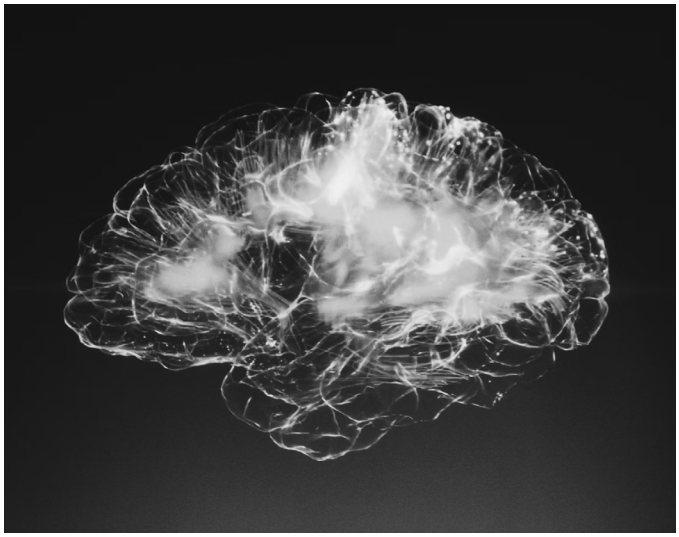
fNIRS signals are vulnerable to artifacts that can compromise data quality. Implement these best practices to minimize errors:

- **Ambient Light Interference**
  External light sources can distort readings. Use shielded environments, conduct regular calibration, and maintain consistent lighting conditions during experiments

- **Technological Cross-Talk**
  Devices such as eye trackers or VR headsets may interfere with fNIRS signals. Position equipment carefully and ensure synchronization between devices to avoid signal contamination. We encourage you to consult with iMotions for further details on the potential technological cross-talk.

- **Motion Artifacts**
  Participant movement can disrupt signal quality. Secure optode placement, instruct participants to minimize movement, and use motion monitoring systems to detect and correct artifacts during analysis.





Summary & Key Takeaways

To maximize the reliability of your fNIRS research:

- **Choose an appropriate experimental design:** block, event-related, or resting-state.
- **Match your fNIRS setup to the scope of your study:** probed or whole-brain.
- **Account for technical limitations, such as hemodynamic delays and spatial depth.**
- **Synchronize data streams when using multiple modalities.**
- **Mitigate potential errors from ambient light, device interference, and motion artifacts.**

By addressing these considerations, researchers can optimize fNIRS technology to produce high-quality, reliable data for neuroscience studies.

9 How iMotions supports fNIRS research

iMotions is a versatile and user-friendly platform that empowers multimodal biosensor research, making it a powerful tool for fNIRS studies. While fNIRS excels at measuring brain activity, it does not directly capture emotional states, attentional shifts, or behavioral responses. Integrating fNIRS with other biosensors, such as eye-tracking, physiological measures, and video monitoring, through iMotions provides a more holistic view of human behavior and cognition.

Simple Sensor Integration

One of iMotions' standout features is its simple sensor integration of fNIRS devices via the Lab Streaming Layer (LSL). This integration ensures smooth synchronization of data across multiple sensors, solving a common challenge in multimodal research: aligning disparate data streams. By utilizing precise, millisecond-based timestamps, iMotions automatically synchronizes all recorded data, enabling researchers to link physiological signals, neural activity, and external behaviors with high accuracy.

iMotions' in-built advanced study builder and the possibility to connect with third party stimulus presentation tools to meet more complex and customized study protocols further streamline fNIRS research, enabling easy design and swift setups. The in-built data analysis tools enable researchers to quickly segment periods of interest for further analysis.

Comprehensive Multimodal Research

Pairing fNIRS with EEG can offer a powerful way to gain a more comprehensive understanding of brain activity. iMotions supports unlimited simultaneous sensor recordings, making it particularly well-suited for complex experiments. For example:

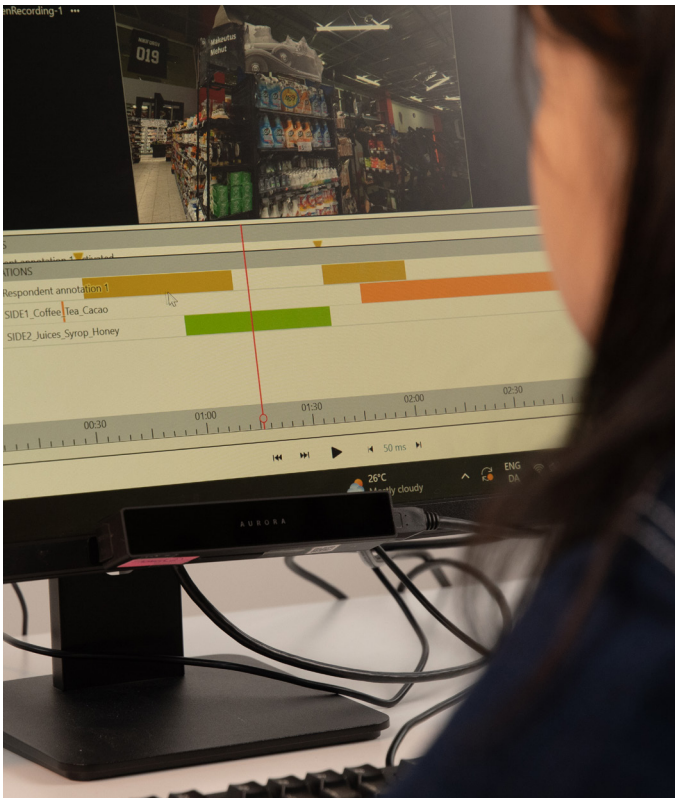
- Pairing fNIRS with **eye-tracking** can illuminate how visual attention correlates with brain activity.
- Integrating **GSR (galvanic skin response)** can provide insights into emotional arousal alongside neural engagement.

- Using **facial coding** can link emotional expressions to underlying brain processes.
- Combining fNIRS with **EMG (electromyography)** can provide insights into muscle movements and co-occurring brain processes.

This multimodal capability allows researchers to uncover intricate relationships between neural activity and external behaviors, creating richer datasets for analysis.

Behavioral Insights with Real-Time Video & Coding

An essential aspect of human research is observing behavior as it unfolds. iMotions facilitates this by synchronizing up to three video streams with biosensor data, enabling researchers to capture and analyze real-time behaviors alongside fNIRS recordings. The platform's manual and automated coding tool options streamline the identification of specific behaviors and their linkage to physiological and neural responses, providing valuable insights into context-driven brain activity. Additionally, iMotions' API allows seamless integration with other behavioral analysis software, such as PsychoPy and E-Prime. This capability lets researchers expand their biosensor setups without altering their established behavioral analysis protocols other behavioral analysis software, such as PsychoPy and E-Prime. This capability lets researchers expand their biosensor setups without altering their established behavioral analysis protocols.



Streamlined Data Export and Analysis

iMotions simplifies data management by supporting easy export of fNIRS data. iMotions provides two types of fNIRS exports:

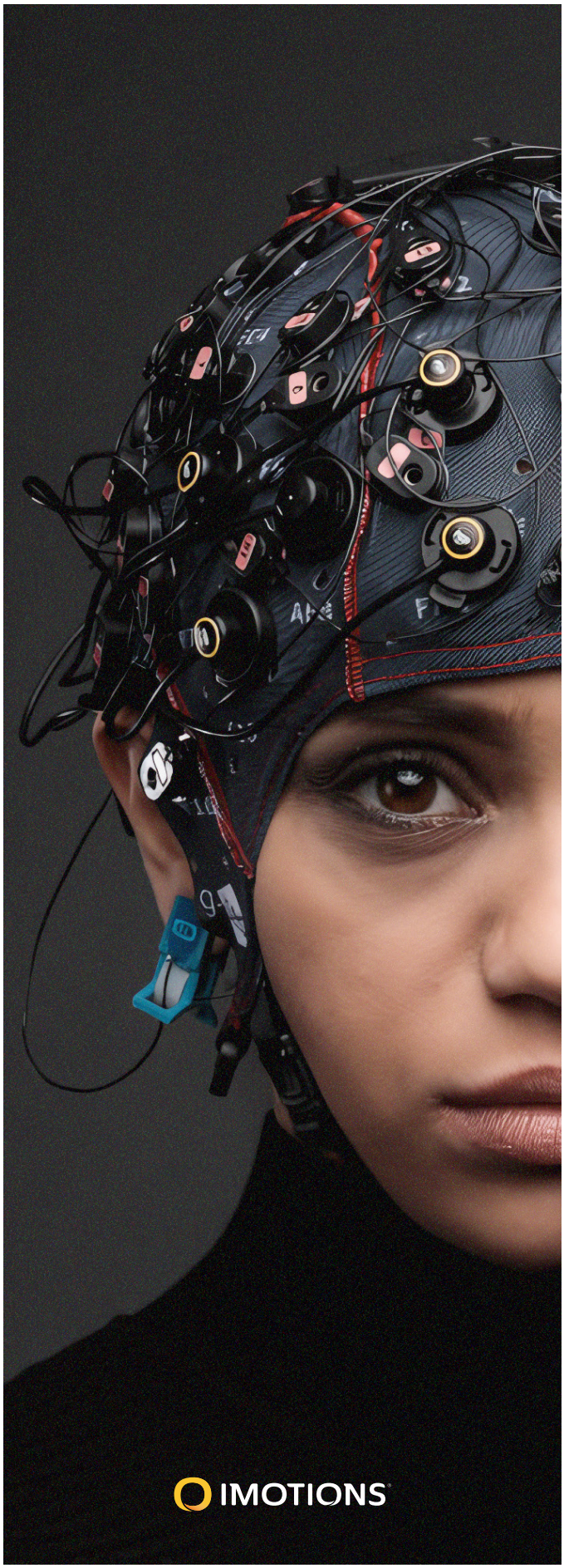
1. **Standard Sensor Data (.csv):**
   Includes all raw sensor data in a .csv format. This includes the fNIRS data as well as any other sensor included in the study, as well as study metadata, signal metadata, event timestamps, and markers from experimental conditions.
2. **Shared Near Infrared Spectroscopy Format (.snirf):**
   Exports fNIRS data, markers, probe information, and preprocessing results from other modalities. This .snirf export can be used with dedicated toolboxes like Homer, FieldTrip, and MNE-Python.

It is recommended to utilize the **.snirf** format with compatible toolboxes which adhere to scientific reporting standards. This flexibility allows researchers to process, analyze and visualize their data with advanced tools while ensuring compliance with publication requirements.

Key Benefits of Using iMotions for fNIRS Research

- **Effortless Data Synchronization:** Automates the alignment of multimodal datasets with millisecond precision.
- **Enhanced Multimodal Research:** Combines fNIRS with a range of biosensors for a more comprehensive understanding of human responses.
- **Real-Time Behavioral Analysis:** Links neural activity to behaviors captured through synchronized video and automated coding.
- **Flexible Data Handling:** Simplifies export to open-source analysis tools, streamlining workflows.

With its robust features, iMotions transforms fNIRS research into a powerful multimodal approach, offering deeper insights into the complexities of human cognition and behavior. Whether you're studying brain activity, emotional responses, or behavioral patterns, iMotions provides the tools to integrate and analyze diverse data sources seamlessly.



Final Words

10

Functional near-infrared spectroscopy (fNIRS) is a powerful tool that enables researchers to delve into the complexities of brain activity, offering valuable insights into human behavior and cognitive processes. Its ability to noninvasively measure cortical activity makes it a practical and adaptable choice for diverse research applications.

By integrating fNIRS with other biosensors, such as eye tracking, galvanic skin response, or video analysis, researchers can uncover deeper, multimodal insights that enhance understanding of the connections between neural activity, emotional experiences, and external behavior. As fNIRS continues to evolve, platforms like iMotions simplify its adoption by offering seamless integration, precise synchronization, and streamlined workflows, empowering researchers to focus on advancing science. Whether exploring individual cognition or dynamic interactions, fNIRS opens new doors for impactful and innovative research.

Discover How to Use fNIRS in Your Research:

IMOTIONS®

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