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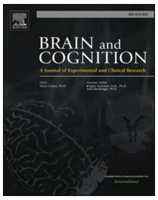

Lights on music cognition: A systematic and critical review of fNIRS applications and future perspectives

Federico Curzel[a,b,*], Barbara Tillmann[b,c], Laura Ferreri[d,a,**]

[a] Laboratoire d'Étude des Mécanismes Cognitifs (EMC), Université Lumière Lyon 2, Bron, Auvergne-Rhône-Alpes, 69500, France
[b] Lyon Neuroscience Research Center (CRNL), INSERM, U1028, CNRS, UMR 5292, Université Claude Bernard Lyon1, Université de Lyon, Bron, Auvergne-Rhône-Alpes, 69500, France
[c] LEAD CNRS UMR5022, Université de Bourgogne-Franche Comté, Dijon, Bourgogne-Franche Comté 21000, France
[d] Department of Brain and Behavioural Sciences, Università di Pavia, Pavia, Lombardia 27100, Italy

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ABSTRACT

Research investigating the neural processes related to music perception and production constitutes a well-established field within the cognitive neurosciences. While most neuroimaging tools have limitations in studying the complexity of musical experiences, functional Near-Infrared Spectroscopy (fNIRS) represents a promising, relatively new tool for studying music processes in both laboratory and ecological settings, which is also suitable for both typical and pathological populations across development. Here we systematically review fNIRS studies on music cognition, highlighting prospects and potentialities. We also include an overview of fNIRS basic theory, together with a brief comparison to characteristics of other neuroimaging tools. Fifty-nine studies meeting inclusion criteria (i.e., using fNIRS with music as the primary stimulus) are presented across five thematic sections. Critical discussion of methodology leads us to propose guidelines of good practices aiming for robust signal analyses and reproducibility. A continuously updated world map is proposed, including basic information from studies meeting the inclusion criteria. It provides an organized, accessible, and updatable reference database, which could serve as a catalyst for future collaborations within the community. In conclusion, fNIRS shows potential for investigating cognitive processes in music, particularly in ecological contexts and with special populations, aligning with current research priorities in music cognition.

1. Introduction

Music is one of the most universal and enjoyable activities for humans. Over the last 50 years, there has been an exponential increase in music cognition studies aiming at revealing how the brain processes music as well as the potential effects of music on the brain. The attention that music has attracted from psychology and neuroscience research stems from the potential of music to boost human cognitive functioning (e.g., Bigand & Tillmann, 2022) and well-being (e.g., Mas-Herrero et al., 2023) with strong implications for neuroscience-informed musical interventions in clinical domains (e.g., Sihvonen et al., 2017; Thaut et al., 2014). Accordingly, techniques and experimental methods have been increasingly developed to investigate the neural and cognitive mechanisms underpinning music perception and production (e.g., Zatorre, 2005).

On a neural level, converging evidence has shown that music activities are related to the activation of a broad network of cortical and subcortical brain areas that are involved in numerous auditory, cognitive, sensory-motor and emotional functions (Koelsch, 2011; Särkämö et al., 2013). The choice of an appropriate neuroimaging technique for investigating the complexity of music-related mechanisms constitutes therefore a challenge in music cognition research. Ideally, the chosen technique for music paradigms would be silent, free of movement constrictions, portable, non-invasive and with good temporal and spatial resolution (Tervaniemi, 2023; Vanzella et al., 2019). These features are hard to find all at once in neuroimaging techniques. For instance, functional Magnetic Resonance Imaging (fMRI) provides a good spatial resolution and also allows for monitoring deep brain structures, for example, involved in musical emotions (e.g., Koelsch, 2014). However,

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* Corresponding author at: Université Lumière Lyon 2 - Laboratoire d'Étude des Mécanismes Cognitifs (EMC), 5 avenue Pierre Mendès France, 69500 Bron cedex, France.
** Corresponding author at: Università di Pavia - Department of Brain and Behavioural Sciences, Piazza Botta, 6, 27100 Pavia, Italy.
E-mail addresses: federico.curzel@univ-lyon2.fr (F. Curzel), barbara.tillmann@cnrs.fr (B. Tillmann), laura.ferreri@unipv.it (L. Ferreri).

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fMRI requires participants to be constrained, with very limited movements allowed (such as finger tapping, or reduced movements of the limbs), in a small and noisy environment, potentially interfering with musical stimulation, and timing resolution is rather coarse. Methodological approaches with the aim to minimizing the noise-constraints, like sparse sampling, are available. Nevertheless, they only reduce the frequency of appearance of the noise, which still occurs with each image acquisition (Hall et al., 1999). Electroencephalography (EEG) allows for non-invasively monitoring of the temporal dynamics of music, such as in rhythm perception (e.g., Nozaradan, 2014). However, EEG is very sensitive to movements, leading to signal artefacts, or hindering individuals' propensity to move in response to music. Within the vast range of neuroimaging techniques, functional Near-Infrared Spectroscopy (fNIRS) arises as a promising and reliable candidate for partially overcoming these issues (Table 1). This technique allows quantifying cortical oxygenation and hemodynamics by harnessing the interaction of near infrared light with the absorption properties of human tissue (Jöbsis, 1977). Although relatively recent, it has experienced a rapid growth in terms of technical development, allowing researchers to monitor brain activity in a wide range of applications and populations over the last years (Cutini & Brigadoi, 2014; Ferreri et al. 2014a; 2014b; Pinti et al., 2020).

The present systematic review builds on the growing body of research conducted over the past two decades that employed fNIRS to investigate the neural underpinnings of music processing. This review aims to provide an overview of the main applications of fNIRS in studying cognitive processes of music perception, appreciation, and various interactions with music, as well as to highlight the main advantages and prospects of its use in this research domain. We first outline the fundamental principles and potentialities of fNIRS. We then present the research studies included in the review organized into five thematic sections: 1) musical activities and expertise, 2) music listening and associated cognitive processes, 3) clinical implications of music and fNIRS, 4) music and development, and 5) music and social cognition. We conclude by providing advices and methodological guidelines for employing fNIRS to investigate music processing in future research.

2. Basic principles of fNIRS

fNIRS is an optical neuroimaging technique that allows for monitoring the neural activity in a noninvasive fashion. It uses light in the near-infrared (NIR) spectrum (650–950 nm) to track the concentration changes of oxygenated (HbO_2) and deoxygenated (HbR) hemoglobin, reflecting oxygen metabolism in the brain tissue. This is achieved by exploiting the absorption properties of human tissue components, in particular of hemoglobin, which is the most dominant and light-absorbing chromophore within the brain tissue (Jöbsis, 1977). The hemoglobin's absorbing properties change according to its oxygenation state: HbO_2 and HbR absorb light mainly at wavelengths > 805 and $<$ 805 nm, respectively (where 805 represents the isosbestic point, in which HbO_2 and HbR have identical absorption coefficients). fNIRS functioning is based on the so-called neurovascular coupling (Villringer et al., 1997), where increased neural activity results in increased demand for oxygen metabolism (Scholkmann et al., 2014), translated in increased cellular oxygen consumption. This triggers local changes in cerebral hemodynamics, inducing an intensified blood flow to the activated brain regions (Izzetoglu et al., 2007; Scholkmann et al., 2014), leading to an increased concentration of HbO_2 and a decreased concentration of HbR (Buxton, 2009). These processes induce regional changes in light attenuation that can be detected by fNIRS and constitute an indirect marker of regional brain activation. In particular, when NIR light is projected by an emitter onto a given region of the head and travels through the skull, it undergoes phenomena of absorption, diffusion, and scattering, which contribute to the light attenuation (Scholkmann et al., 2014). The different absorption properties of HbO_2 and HbR, and the use of light with two or three specific wavelengths (usually one above and one below the isosbestic point), allow for the non-invasive quantification of their concentration change (via the modified Beer-Lambert law; Baker et al., 2014; Delpy et al., 1988; Izzetoglu et al., 2007). The non-absorbed components of the emitted light are measured through a detector placed at approximately 3 cm from an emitter along the surface of the skull. Emitters and detectors are also generically called "optodes", and the pairing between an emitter and a detector constitutes a "channel". It is noteworthy that the probabilistic path of NIR light (i.e., the optical pathlength) is longer than the

Table 1
Comparison of fNIRS with other common neuroimaging techniques.

Technique	fNIRS	fMRI	PET	EEG	MEG
Full Name	Functional Near-Infrared Spectroscopy	Functional Magnetic Resonance Imaging	Positron Emission Tomography	Electro-encephalography	Magneto-encephalography
Measurement	Indirect: HbO, HbR	Indirect: BOLD (HbR)	Direct: CBF, glucose metabolism	Direct: Electromagnetic	Direct: Electromagnetic
Spatial Resolution	Moderate (1–3 cm)	High (1–2 mm)	High (4–5 mm)	Low (5–9 cm)	High (2–3 mm)
Temporal sampling rate	High (up to 100 Hz)	Moderate (1–3 Hz)	Low (<0.1 Hz)	High (>1000 Hz)	High (>1000 Hz)
Depth of measurement	Cerebral cortex (1.5——2 cm)	Whole brain	Whole brain	Cortical surface (1–5 mm)	Cortical surface
Material Compatibility	No compatibility problems are reported	Limited (no metals, implants, and devices)	Various; may require shielding for radiation protection	No compatibility problems are reported	Compatible with non-metallic materials
Tolerance to movement	Good	Limited	Limited	Limited	Limited
Portability	Yes, for portable systems	No	No	Yes, for portable systems	No, but portable systems are in development
Sounds	Silent	Very noisy	Silent	Silent	Silent
Cost	Low	High	Very high	Low	High
Possible participants	Everyone	Limited (challenging for infants, children, elderly, patients)	Limited	Accessible (but difficult with toddlers, people with cochlear implants or hearing aids, and patients)	Everyone (but difficult with infants and patients)
Characteristics for Music Cognition studies	Non-invasiveness, portability, suitable for naturalistic musical experiences	High spatial resolution, whole-brain coverage, complex brain network investigation	Quantitative measurement of neurotransmitters in musical processing	High temporal resolution, suitable for monitoring rapid changes in brain activity	High temporal resolution, capturing fast oscillatory responses; source localization

physical distance of a channel, as part of the light can penetrate through the tissue forming the so-called “banana shape” profile (Ferrari & Quaresima, 2012; see also Fig. 1). The longer a channel (with an optimum length between 3–4 cm in adults and 2 – 2.5 cm in infants), the deeper light can travel (to an approximate distance of half of the emitter-detector distance; Patil et al., 2011). However, increasing the emitter-detector distance increases the signal-to-noise ratio, leading to a progressive loss of signal (Calderon-Arnulphi et al., 2009).

The most common commercially available fNIRS systems, which are used in research, are the so-called continuous-wave devices. A continuous NIR light beam projected onto the brain allows assessing the light attenuation (i.e., the difference between the emitted and detected light), but does not allow determining absolute concentration changes, as these devices cannot quantify the independent contribution of absorption and scattering. Determining absolute concentration changes is possible with the more advanced time-domain or frequency-domain fNIRS systems, using respectively light sources firing pulses at a timescale of picoseconds (for further details see Torricelli et al., 2014), and intensity-modulated light at very high frequencies signals (for further details see Fantini & Sassaroli, 2020; Wolf et al., 2007). Other recent systems enable enhanced spatial resolution thanks to the development of High-Density Diffuse Optical Tomography (HD-DOT) systems, which incorporate high-density optode arrays (Eggebrecht et al., 2014). Specifically, a quantitative voxel-wise comparison of HD-DOT and fMRI (using a 3 T scanner with 3 mm isotropic voxels) showed an average localization error of only 4.4 ± 1 mm, indicating high spatial accuracy of HD-DOT relative to the fMRI standard (Eggebrecht et al., 2012). Comparing the spatial alignment of measures from continuous-wave devices with fMRI measures revealed a strong correspondence at the group level, suggesting their reliability for clinical use (Klein et al. 2022a; Toronov et al. 2007; Zinos et al., 2024). fNIRS systems are available as either full-head or partial-head systems. Depending on the number of channels available and their geometric organization, regions of the cerebral cortex of different sizes and location can be measured (see section 6.2.1. *Choice of brain areas and optode placement* for details and practical advice).

Thanks to a set of attractive features, fNIRS systems constitute a reliable neuroimaging technique for the study of human cognition (Cutini & Brigadoi, 2014; Ferreri et al., 2014a; 2014b; Yücel et al., 2017). To prove its reliability, the neural activity measured with fNIRS has been compared to the blood-oxygenation-level-dependent (BOLD) signal measured with fMRI by several studies, finding positive correlations with HbO_2 as well as anti-correlations with HbR (Duan et al., 2012; Eggebrecht et al., 2012; Huppert et al., 2006; Noah et al., 2015; Scarapicchia et al., 2017; Steinbrink et al., 2006; Q. Wang et al., 2020). fNIRS is portable (and in some cases wireless; Pinti et al., 2018; Zhao & Cooper, 2017), non-invasive, silent, resistant to motion artifacts, and relatively inexpensive, thus presenting numerous advantages over other neuroimaging techniques (Table 1). It is also compatible with other neuroimaging or neurostimulation tools, thus enabling multimodal acquisitions (Di Rosa et al., 2019; Qiu et al., 2022; Ru et al., 2022). In particular, the coupling of fNIRS with EEG is increasingly employed. It complements the strengths of both techniques and enables a more detailed picture of brain activity by monitoring both cortical hemodynamics and electrical activity, while maintaining portability and non-invasiveness (R. Li et al., 2022). The combination of fNIRS and MEG is also feasible and has been used to investigate the neurovascular coupling process (Ou et al., 2009). The simultaneous acquisition of fNIRS and fMRI (Gagnon et al., 2011) or PET (Rostrup et al., 2002) allows for detailed study and quantification of the hemodynamic response. Other complex combinations have also been reported, such as simultaneous acquisitions of fNIRS, EEG and fMRI (Anwar et al., 2016), or fNIRS, EEG, and MEG (Ru et al., 2022). Concerning the coupling with neurostimulation tools, fNIRS can efficiently measure the cortical activity after stimulation with transcranial direct or alternate current stimulation (Di Rosa et al., 2019; Ghafoor et al., 2022) or transcranial magnetic stimulation (Curtin et al., 2019). Numerous studies have shown that fNIRS is an optimal tool for investigating motor and auditory tasks in typical and pathological populations across development (Gervain et al., 2023; Gramigna et al., 2017; Perrey, 2008; Shatzer & Russo, 2023; Wang et al., 2020). Therefore, fNIRS emerges as particularly suitable for music cognition studies in both laboratory and clinical settings (Chen et al., 2020), including naturalistic and interactive environments (Pinti et al., 2020; Yücel et al., 2017).

3. Methods

Methods were registered on PROSPERO[1] (ID number: CRD42022349998) before starting the search.

3.1. Search strategy

Two of the authors independently collected data from a systematic search on electronic databases, including PubMed, Scopus, Google Scholar, APA PsycNet and Web of Science in October 2022. The search aimed to identify all studies on music cognition conducted with fNIRS. The search strategy involved a combination of the following keywords: ‘fNIRS & music’ and ‘functional near-infrared spectroscopy & music’. All studies found in the databases were collected using Zotero for reference management and then exported into a single Excel file.

3.2. Inclusion criteria

All experimental studies using fNIRS as the principal neuroimaging technique and using musical stimuli in the procedure were included at first. Studies written in non-English languages or not employing specific musical stimuli (e.g., those using background noise or white noise stimuli) were then excluded (see Fig. 2). Duplicate articles (i.e., those found in multiple databases) were also removed.

3.3. Study selection

Two authors independently reviewed the titles and abstracts of potentially eligible articles. Any selected article that was ambiguous for inclusion in the first selection (see section 3.2. *Inclusion criteria*) was discussed in the presence of the third author. In the next step, the authors performed a full-text reading, and the third author was involved in cases of ambiguity. The PRISMA flowchart was used for data synthesis (see Fig. 2).

3.4. Data extraction

For each included article, the following information was extracted: title, author, country and year of the study, number of participants and their musical expertise, age and sex, diagnoses (for patient populations only), type of fNIRS system used, manufacturer and number of channels, regions of the brain that were investigated, study design, type and duration of the stimulus, tasks performed, and main findings.

3.5. Risk of bias assessment

All studies eligible for inclusion were assessed for quality using a checklist designed by the authors and declared in PROSPERO. The quality assessment was performed independently by two authors and conflicts were resolved in the presence of a third author when necessary.

4. Results

Fifty-nine articles were included in this review (see PRISMA chart, Fig. 2): 14 concerned musical activities and expertise, 22 music listening

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[1] https://www.crd.york.ac.uk/prospero/.

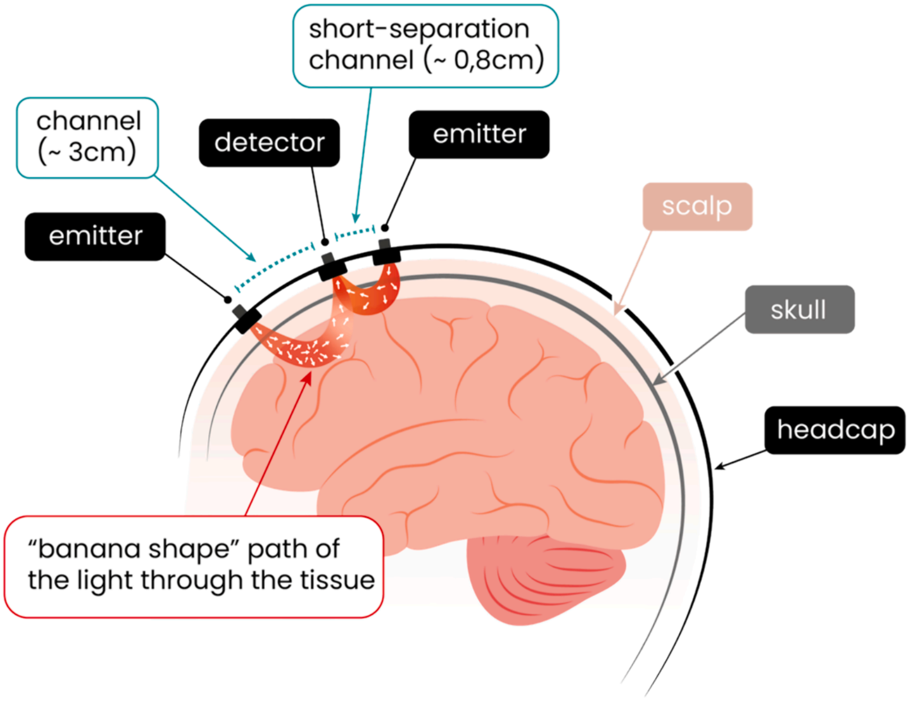

Fig. 1. Illustration of a simplified fNIRS montage. Emitters positioned above the scalp emit light perpendicular to the skull. Detectors measure the unabsorbed components of light, after its passage in the assumed "banana-shape" path through the underlying tissues, undergoing phenomena of absorption, diffusion, and scattering (depicted by the white arrows). Each emitter-detector pair constitutes a channel; the so-called short-separation channels (approximately 0.8 cm) measure the light absorbed by extracortical tissues. Their signal can be then subtracted from the one measured by longer channels (approximately 3 cm), thus allowing the isolation of the light absorbed specifically by cortical tissue. A demonstration video showing a portable fNIRS system, optode placement, signal acquisition, and examples of both a solo and shared music listening task in hyperscanning is available here: https://osf.io/uqkfr/?view_only=64cd2976c14c4f199aa0e4188cff4489.

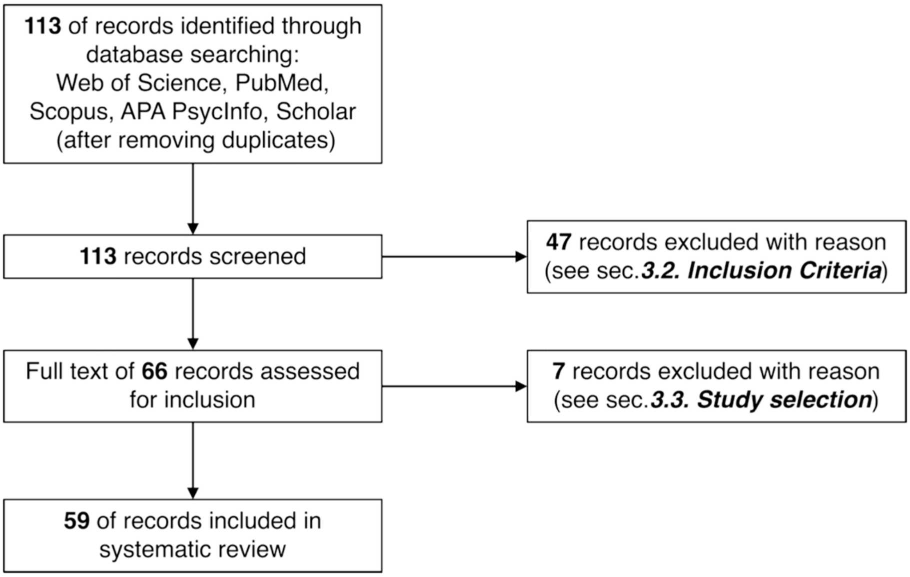

Fig. 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist and flow diagram with details of the search, screening, and selection processes for identifying relevant articles in this review.

and associated cognitive processes, 9 clinical implications of music and fNIRS, 7 music and development, and 7 music and social cognition. Information was extracted from the articles as described in section 3.4. *Data extraction*, presented in Table 2, and discussed in section 5. *fNIRS and music cognition.*

5. fNIRS and music cognition

Research in music cognition requires neuroimaging tools that need to overcome limiting features, such as restrictive, still-holding postures as well as constant background noise from instruments, which could potentially interfere with musical stimuli. fNIRS offers a valid solution for overcoming these challenges, allowing experiments to be run in ecological settings (Balardin et al., 2017b) and with various populations,

Table 2
Information extracted from the studies included in the present review and further described in sections 5.1 to 5.5. The order of studies' appearance in the table reflects that in the text. N.R. = not reported / unclear information in the original work, SS channels = short-separation channels, FC = frontal cortex, PFC = prefrontal cortex, MPFC = medial prefrontal cortex, LPFC = lateral prefrontal cortex, rLPFC = right lateral prefrontal cortex, DPFC = dorsal prefrontal cortex, DLPFC = dorsolateral prefrontal cortex, VLPFC = ventrolateral prefrontal cortex, FPC = frontopolar cortex, OFC = orbitofrontal cortex, AC = auditory cortex, STG = superior temporal gyrus, TP = temporo-parietal, TPJ = temporo-parietal junction, lTPJ = left temporo-parietal junction, IFG = inferior frontal gyrus, MTG = middle temporal gyrus, OL = occipital lobe, ROL = rolandic operculum, PreCG = precentral gyrus, SPL = superior parietal lobule, TL = temporal lobe, STG = superior temporal gyrus, SMG = supramarginal gyrus, PoCG = postcentral gyrus, SMA = supplementary motor area, PCL = paracentral lobule, lIMC = left inferior motor cortex, PMC = premotor cortex, MC = motor cortex.

Section	Authors	Country	Sample Characteristics – Number of Participants (n) / Mean Age in years ± SD – Musical education or skills (mean years ± SD)	Type of fNIRS system: model (manufacturer) – Number of channels/ Number of SS channels; Eventual other neuro-imaging/-stimulation tools coupled	Regions of Interest (ROIs)	Study design (block or event related / between or within subjects) – Stimulus duration	Task performed
5.1) Musical activities and expertise	Hashimoto et al., 2006	Japan	Healthy participants – 7 (7 females)/24.1 ± 7.9 – Musicians (14.3 ± 0.3)	**CW-NIRS**: SHIMADZU – 32/0	FL	Block design/N.R. – N.R.	***Piano*** playing and bimanual performance of memorized musical scales
	Yuksel et al., 2016	USA	Healthy participants – 16 (8 females)/21 ± 2.4 – Musicians (Information on musical education and skills N.R.)	**CW-NIRS**: Imagent (ISS, Champaign, Illinois) – 8/0	PFC	Block design/ within subject – 30 s	Playing musical pieces of varying difficulty on the ***piano***
	Alves Heinze et al., 2019	Brazil	Healthy participants – 15 (5 females)/21.5 ± 2.4 – None of them had previous experience playing keyboard instruments	**CW-NIRS**: NIRSport8x8 system, NIRx – 20/0	PFC	Block design/ within subject – 30 s	Participants learned to play a sequence of three chords on a ***piano*** keyboard and rated the felt difficulty at each block
	Curzel et al., 2021	Italy	Healthy participants – 34 (23 females)/21.27 ± 2.74 – Non musicians (0)	**CW-NIRS**: Imagent (ISS, Champaign, Illinois) – 44/2	STG, MTG, ROL, PreCG, SMG, PoCG, SMA, PCL	Block design/ within subject – 18 s	Rhythmic auditory cueing short-term training with an electronic ***drum (e-drum)***
	Ono et al., 2014 (for comparison with fMRI results see Noah et al., 2015)	Japan	Healthy participants – 26 (5 females)/26.1 ± 1.7 – Various levels of experience playing a specific dance video game	**CW-NIRS**: OMM-3000 (Shimadzu Co., Kyoto, Japan) – 22/0	FPC, MTG	Block design/ within subject – 30 s	***Dance*** simulation video game: task involved pressing arrow buttons with the foot in response to moving arrows
	Tachibana et al., 2011	Japan	Healthy participants – 7 (1 female)/23–32 ± (SD N.R.) – Various levels of experience playing a specific dance video game	**CW-NIRS**: ETG-7100 (Hitachi Medical Co., Kashiwa, Japan) – 48/0	SPL, STG	Block design/ within subject – 30 s	***Dance*** simulation video game: task involved pressing arrow buttons with the foot in response to moving arrows
	Tachibana et al., 2019	Japan	Healthy participants – 20 (0 females)/ 34.5 ± 13.3 – Amateur or professional musicians (3–43 years of practice)	**CW-NIRS**: ETG-7100 (Hitachi Medical Co., Kashiwa, Japan) – 48/0	PFC	Block design/ within subjects – 40 s	Blues rock improvisation on ***guitar***
	Lo et al., 2009	Singapore	Healthy participants – 31 (0 females)/25–36 ± (SD N.R.) – Information on musical education and skills N.R.	**CW-NIRS**: NIRO-200 Niro Monitor (Hamamatsu Photonics KK, Japan) – 9/0; TMS: Magstim 8-shaped magnetic coil (Magstim Company, Whitland, UK)	lIMC	Block design/ within subjects – 120 s	Reading and ***singing***
	Gibson et al., 2009	USA	Healthy participants – 8 (5 females)/19.7 ± 1.2 – Musicians 7 (4 females)/19.1 ± 1.3 – Non musicians	**CW-NIRS**: ETG-100 (Hitachi Medical Co., Kashiwa, Japan) – 22/0	PFC	Block design/ within subjects – 30 s/45 s	Divergent thinking test
	Wakita, 2014	Japan	Healthy participants – 20 in total: 10 (10 females)/28.7 (SD N.R.) – Expert musicians (11.4 years of piano lessons) 10 (8 females)/29.9 ± (SD N.R.) – Novice musicians (3.4 years of piano lessons)	**CW-NIRS**: ETG-100 (Hitachi Medical Co., Tokio, Japan) – 12/0	IFG	Block design/ within subjects – 16 s	Observation of a silent video showing a hand playing a familiar vs unfamiliar melody on the piano

(continued on next page)

Table 2 (*continued*)

Section	Authors	Country	Sample Characteristics – Number of Participants (n) / Mean Age in years ± SD – Musical education or skills (mean years ± SD)	Type of fNIRS system: model (manufacturer) – Number of channels/ Number of SS channels; Eventual other neuro-imaging/-stimulation tools coupled	Regions of Interest (ROIs)	Study design (block or event related / between or within subjects) – Stimulus duration	Task performed
	Falk et al., 2011	Canada	Healthy participants – 10 (7 females)/31.5 ± 10.8 – Information on musical education and skills N.R.	**FD-NIRS**: Imagent (ISS, Champaign, Illinois) – 8/0	PFC	Block/Event-related design/ within subjects – Music imagery task: 20 s/Block	Music imagery tasks
	Power et al., 2010	Canada	Healthy participants – 10 (6 females)/26.2 ± 6.9 – Information on musical education and skills N.R.	**FD-NIRS**: Imagent (ISS, Champaign, Illinois) – 9/0	PFC	Block design/ within subjects – 20 s	Music imagery (mental singing) and mental arithmetic tasks
	Power et al., 2011	Canada	Healthy participants – 8 (6 females)/25.9 ± 2.9 – Information on musical education and skills N.R.	**FD-NIRS**: Imagent (ISS, Champaign, Illinois) – 9/0	PFC	Block design/ within subjects – 20 s	Music imagery (mental singing), multiple choice tasks, and mental arithmetic tasks
	Power et al., 2012	Canada	Healthy participants – 7 (2 females)/25.7 ± 3.1 – Information on musical education and skills N.R.	**FD-NIRS**: Imagent (ISS, Champaign, Illinois) – 9/0	PFC	Block design/ within subjects – 20 s	Mental imagery (mental singing) and mental arithmetic tasks
5.2) Music listening and associated cognitive processes	Daikoku et al., 2012	Japan	Healthy participants – 10 (6 females)/20.7 ± 0.6 – Musicians (7.8 ± 2.9 years of lessons) 10 (4 females)/21.0 ± 1.2 – Non musicians	**CW-NIRS**: ETG-4000 (Hitachi Medical Corp., Tokyo, Japan) – N.R.	STG	Block design/ within subjects – 32 s	Listening to consonant and dissonant chords progressions
	Santosa et al., 2014	South Korea	Healthy participants – 14 (7 females)/28 ± 5 – of which, 3 Musicians (16 ± 2 years of musical training)	**CW-NIRS**: DYNOT (NIRx Medical Technologies, Brooklyn, NY) – 22/0	AC	Block design/ within subject – 15 s	Listening to music and noise separately or mixed
	Yoo et al., 2021	South Korea	Healthy participants – 18 (7 females)/ 26.9 ± 3.5 – Information on musical education and skills N.R.	**CW-NIRS**: DYNOT (NIRx Medical Technologies, Brooklyn, NY) – 22/0	AC	Block design/ within subject – 10 s	Listening to different auditory stimuli (music, speech, annoying sound, nature sound, gunshot)
	Rossi et al., 2020	Austria	Healthy participants – 20 (10 female)/ 38.7 ± range 28–53 – No professional musicians included	**CW-NIRS**: NIRScout (NIRx Medical Technologies, LLC, USA) – 14/0 **EEG**: (Brain Products GmbH, Gilching, Germany); 13 electrodes	PFC, TP	Event-related design/within subject – 3 s	Listening to semantically correct and incorrect spoken and sung sentences
	Jeong & Ryu, 2016b	South Korea	Healthy participants – 25 (7 females)/23.7 ± 2.0 – Non musicians	**CW-NIRS**: Spectratech OEG-16 (Shimadzu Co. Ltd., Kyoto, Japan) – 16/0	FPC, LPFC	Block design/ within subjects – ~1s	Listening to different sounds (tones, timbres, words, syllables) and identification of their presentation order
	Jeong et al., 2018a	South Korea	Healthy participants – 16 (6 females)/23.5 ± 1.7 – Any professional musician (less than 1 year of formal training)	**CW-NIRS**: Spectratech OEG-16 (Shimadzu Co. Ltd., Kyoto, Japan) – 16/0	FPC, LPFC	Block design/ within subject – N.R.	Melodic contour identification task (CIT)
	Ferreri et al., 2013	France	Healthy participants – 22 (11 females)/ 23.5 ± 4.3 – Non musicians	**CW-NIRS**: Oxymon MkIII (Artinis Medical Systems B.V., The Netherlands) – 8/0	DLPFC	Block design/ within subject – 28 s	Listening to music and encoding list of words
	Ferreri et al., 2014b	France	Healthy participants – 16 (10 females)/ 64.5 ± 2.5 – Non musicians	**CW-NIRS**: Oxymon MkIII (Artinis Medical Systems B.V., The Netherlands) – 8/0	DLPFC	Block design/ within subject – 28 s	Listening to music and encoding list of words
	Ferreri et al., 2015	France	Healthy participants – 19 (13 females)/21.7 ± 3.2 – Non musicians	**CW-NIRS**: Oxymon MkIII (Artinis Medical Systems B.V., The Netherlands) – 48/0	PFC	Block design/ within subject – Encoding 45 s/ Retrieval 30 s	Listening to music, encoding list of words and free recall of them
	Bigliassi, 2015	Brazil	Healthy participants – 18 (8 females)/22.3 ± 2.3 – Non musicians	**CW-NIRS**: Biopac Systems – 16/0	PFC	Block design/ within subjects – 90 s	Listening to different musical genres
	Da Silva Ferreira Barreto et al., 2020	Brazil	Healthy participants – 40 (16 females)/25.0 ± 5.1 – Information on	**CW-NIRS**: NIRSport (NIRx Medical Technologies) – 20/0	PFC	Block design/ within subjects – 62 s	Listening to classical music

(*continued on next page*)

Table 2 (*continued*)

Section	Authors	Country	Sample Characteristics – Number of Participants (n) / Mean Age in years ± SD – Musical education or skills (mean years ± SD)	Type of fNIRS system: model (manufacturer) – Number of channels/ Number of SS channels; Eventual other neuro-imaging/-stimulation tools coupled	Regions of Interest (ROIs)	Study design (block or event related / between or within subjects) – Stimulus duration	Task performed
			musical education and skills N.R.				
	Moghimi et al., 2012a	Canada	Healthy participants – 9 (5 females)/25.0 ± 2.7 – Information on musical education and skills N.R.	**CW-NIRS**: Imagent (ISS, Champaign, Illinois) – 9/ 0	PFC	Block design/ within subjects – 45 s	Listening to music of different musical genres (experimenter- and participant-selected favorite music)
	Moghimi et al., 2012b	Canada	Healthy participants – 10 (5 females)/25.0 ± 2.7 – Musicians (5.5 years of training)	**CW-NIRS**: Imagent (ISS, Champaign, Illinois) – 9/ 0	PFC	Block design/ within subjects – 45 s	Listening to music of different musical genres (experimenter- and participant-selected favorite music)
	Moghimi et al., 2015	Canada	Healthy participants – 10 (5 females)/25.0 ± 2.7 – Musicians (5.5 years of training)	**CW-NIRS**: Imagent (ISS, Champaign, Illinois) – 9/ 0	PFC	Block design/ within subjects – 45 s	Listening to music of different musical genres (experimenter- and participant-selected favorite music)
	Qiu et al., 2022	China	Healthy participants – 9 (4 females)/31.3 (SD N.R.) – Information on musical education and skills N.R.	**CW-NIRS**: NIRScout system (NIRx Medizintechnik GmbH, Germany) – 44/0; **EEG**: BrainAmp DC (Brain Products GmbH, Germany) – 32 electrodes	PFC, PreCG, SMG	Block design/ within subjects – 120 s	Listening to music of different musical genres (experimenter- and participant-selected favorite music)
	Bandara et al., 2018	USA	Healthy participants – 20 (7 females)/ "college age" (any other information provided) – Information on musical education and skills N.R.	**CW-NIRS**: ETG-4000 (Hitachi Medical Corp., Tokyo, Japan) – N.R.	PFC, SMA, STG, MC, MTG	Block design/ within subjects – 60 s	Listening/watching music videoclips of various genres
	Yamada & Ono, 2019	Japan	Healthy participants – 15 (2 females)/21.7 ± 0.7 – Information on musical education and skills N.R.	**CW-NIRS**: OMM-3000 (Shimadzu Co., Kyoto, Japan) – 38/0	PFC, STG	Block design/ within subjects – 40 s	Listening to music of different musical genres (participant-selected favorite and non-favorite music)
	Bigliassi et al., 2015b	Brazil	Healthy participants – 30 (15 females)/25.0 ± 2.8 – Non musicians	**CW-NIRS**: fNIRS (BIOPAC Systems, Inc., Goleta, CA) – 16/0	PFC	Block design/ within subject – 30 min/each music genre	Listening to classical and techno music
	Bigliassi et al., 2015c	Brazil	Healthy participants – 15 (Information about gender N.R.)/24.9 ± 2.5 – Information on musical education and skills N.R.	**CW-NIRS**: fNIRS (BIOPAC Systems, Inc., Goleta, CA) – 16/0	PFC	N.R.	Listening to participant-selected music
	Fukuie et al., 2022	Japan	Healthy participants – 58 (28 females)/20.2 ± 1.8 – Information on musical education and skills N.R.	**CW-NIRS**: ETG-700 (Hitachi Medical Corporation, Japan) – N.R.	DLPFC, VLPFC, FPC	Block before and after stimulation/ within subject – 6.5 min	Listening to a groovy rhythm
	Suwabe et al., 2021	Japan	Healthy participants – 33 (12 females)/20.9 ± 2.4 – Information on musical education and skills N.R.	**CW-NIRS**: ETG-700 (Hitachi Medical Corporation, Japan) – N.R.	DLPFC, VLPFC, FPC	Long unique block/ within subject – 10 min	Listening to participant-selected favorite music and pedaling
	Bigliassi et al., 2015a	Brazil	Healthy participants – 30 (15 females)/25.0 ± 2.8 – Non musicians	**CW-NIRS**: fNIRS (BIOPAC Systems, Inc., Goleta, CA) – 16/0	PFC	Block design/ within subject – N.R.	Listening to a participant-selected motivational song and an experimenter-selected calm song
5.3) Clinical implications of music and fNIRS	Jeong & Ryu, 2016a	South Korea	Healthy participants – 13 young adults (3 females)/23.5 ± 1.7 – No professional musicians included 14 older adults (7 females)/56.1 ± 6.4 – – No professional musicians included	**CW-NIRS**: Spectratech OEG-16 (Shimadzu Co. Ltd., Kyoto, Japan) – 16/ 0	FPC, DLPFC	Block design/ within subject – N.R.	Melodic contour identification task (CIT; played by piano, flute or string)

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Table 2 (*continued*)

Section	Authors	Country	Sample Characteristics – Number of Participants (n) / Mean Age in years ± SD – Musical education or skills (mean years ± SD)	Type of fNIRS system: model (manufacturer) – Number of channels/ Number of SS channels; Eventual other neuro-imaging/-stimulation tools coupled	Regions of Interest (ROIs)	Study design (block or event related / between or within subjects) – Stimulus duration	Task performed
	Jeong et al., 2018b	South Korea	15 Patients with acquired brain injury (ABI; 2 females)/53.6 ± 8.9 – and, 19.4 ± 33.3 months after the brain injury – < 3 months of musical training 22 Healthy adults (Information about gender N.R.)/55.8 ± 6.0 – Not involved in musical activities/ trainings	**CW-NIRS**: Spectratech OEG-16 (Shimadzu Co. Ltd., Kyoto, Japan) – 16/ 0	FPC, DLPFC	Block design/ within subject – 180 to 360 s	Melodic contour identification task (CIT; played by piano, flute or string)
	Da et al., 2021	Netherlands	15 patients with traumatic brain injury (TBI; 7 females)/11.4 ± 3.5 21 healthy participants (13 females)/10.6 ± 2.4 – Information on musical education and skills N.R.	**CW-NIRS**: PortaLite (Artinis Medical Systems B.V., Elst, The Netherlands) – 3/0	rLPFC	Block design/ within subject – 60/120 s	Listening to classical music and verbal fluency task
	Bicciato et al., 2022	Switzerland	Healthy participants – 6 (2 females)/41.2 ± 12.6 – Information on musical education and skills N.R.	**CW-NIRS**: OXYMON Mk III (Artinis Medical Systems B. V., Elst, The Netherlands) – 2/2	FPC	Block design/ within subject – 120 to 300 s	Listening to participant-selected favourite music
	Feng et al., 2019	China	15 patients with moderate major depressive disorder (MDD; 8 females)/30.9 ± 13.5 – Information on musical education and skills N.R. 15 healthy participants (9 females)/30.9 ± 10.1 – Information on musical education and skills N.R.	**CW-NIRS**: FOIRE3000 (Shimadzu, Kyoto, Japan) – 45/0	PFC	Block design/ within subject – 30 s	Verbal fluency task (VFT) before and after 10 days of a continuous music therapy intervention
	Saitou et al., 2000	Japan	44 patients with hemiplegia (13 females)/66 ± 9.3 – Information on musical education and skills N.R. 24 healthy participants (22 females)/22.6 ± 4.1 – Information on musical education and skills N.R.	**CW-NIRS**: HEO-200 (Omron Co, Ltd, Tokyo, Japan) – 1/0	FPC	Block design/ within subject – N. R.	Listening to classical music, among other common rehabilitation tasks
	Wang et al., 2020	China	Healthy participants – 21 (10 females)/24.6 ± 1.9 – Information on musical education and skills N.R.	**CW-NIRS**: Nirsmart (Danyang Huichuang Medical Equipment Co., Ltd, China) – 40/0	PFC, MC, OL, TL	Block design/ within subject – 80 s	Drumming
	Li et al., 2020	China	Healthy participants – 22 (11 females)/ 24.4 ± 2.1 – Information on musical education and skills N.R.	**CW-NIRS**: Nirsmart (Danyang Huichuang Medical Equipment Co., Ltd, China) – 40/0	PFC, MC, OL, TL	Block design/ within subject – 30 s	Multisensory training with the music rehabilitation glove (MRG)
	Shimizu et al., 2018	Japan	Adults with mild cognitive impairment – 45 (38 females)/74.6 ± 5.1 – Information on musical education and skills N.R.	**CW-NIRS**: LABNIRS (Shimadzu Co., Kyoto, Japan) – 45/0	PFC, OFC	Block design/ between participants – 60 s	Group 1: Music-supported movement therapy Group 2 (control): movement therapy without music
5.4) Music and development	Sakatani et al., 1999	China	Healthy participants (newborns) – 28 (13 females, 6 born preterm)/3.1 ± 0.3 days	**CW-NIRS**: NIRO-500 (Hamamatsu Photonics K. K.) – 1/0	FPC	Long block/within subject – 10 min	Listening to popular piano music
	Fava et al., 2014	USA	Healthy participants – 41 (22 females)/range 4 – 11 months ± (SD N.R.)	**CW-NIRS**: Information about the model and manufacturer N.R. – 4/0	TL	Block design/ within subject – 20 s	Listening to speech and music

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Section	Authors	Country	Sample Characteristics – Number of Participants (n) / Mean Age in years ± SD – Musical education or skills (mean years ± SD)	Type of fNIRS system: model (manufacturer) – Number of channels/ Number of SS channels; Eventual other neuro-imaging/-stimulation tools coupled	Regions of Interest (ROIs)	Study design (block or event related / between or within subjects) – Stimulus duration	Task performed
	Kotilahti et al., 2010	Finland	Healthy participants (newborns) – 13 (4 females)/1.8 ± 1.0 days	**FD-NIRS**: NIRS system developed at Helsinki University of Technology – 16/0	AC	Block design/ within subject – 5 s	Listening to speech and music
	Homae et al., 2012	Japan	Healthy participants – 22 (7 females)/115.5 days ± (range 95–128; SD N.R.) 3-month-old 24 (15 females)/193.8 days ± (range 182–209; SD N.R.) 6-month-old	**CW-NIRS**: ETG-100 (Hitachi Medical Corporation, Tokyo, Japan) for 3-month-old infants – 48/0 ETG-7000 (Hitachi Medical Corporation, Tokyo, Japan) for 6-month-old infants – 64/0	TL, TP	Block design/ within subjects – 4.8 s	Listening to three types of auditory sequences with distinct temporal structures of pitch changes
	Ren et al., 2021	China	Preterm infants – 40 (18 females)/ gestational age = 34.2 ± 1.1 weeks	**CW-NIRS**: NIRScout (NIRx Medical Technologies, LLC., USA) – 19/0	FC, TP, TC	Block design/ between subjects – 180 s	Group 1: Standard cares + Listening to classical music Group 2 (control): Standard cares
	Meder et al., 2021	Hungary	Preterm infants – 31 (16 female)/ gestational age = 30 weeks ± (range 33–36)	**CW-NIRS**: SenSmart Model X-100 (Nonin Medical Inc., Plymouth, MN, USA) – 2/0	TC	Long blocks/within subject – 20 min	Maternal singing accompanied by live guitar music; skin-to-skin contact with the mother
	Kovelman et al., 2012	USA	Healthy participants – 15 (4 females)/7.3 years ± 1.0 – Information on musical education and skills N.R.	**CW-NIRS**: ETG-4000 (Hitachi Medical Corp., Tokyo, Japan) – 22/0	FC, TP	Block design/ within subject – 20 s	Rhythm perception task
5.5) Music and social cognition	Osaka et al., 2015	Japan	Healthy participants – Singing group: 30 (15 dyads, of which 7 female dyads)/22 ± (SD N.R.) – Information on musical education and skills N.R. Humming group: 28 (14 dyads, 5 female dyads)/ 21± (SD N.R.) – Information on musical education and skills N.R.	**CW-NIRS**: LABNIRS (Shimadzu Co., Kyoto, Japan) – 34/0	FC, TC, TP	Block design/ between subjects – 100 s	Singing group: Singing a song alone, listening to the partner's singing or sing with the partner Humming group: identical, with humming instead of singing
	Pan et al., 2018	China	Healthy participants – 24 dyads in total: 24 learners (all females)/ 20.6 ± 2.2 – Non musicians (no formal musical training) 1 instructor (female)/22 – Musician (13 years of music training);	**CW-NIRS**: ETG-7100 (Hitachi Medical Corporation, Japan) – 22/0	FC, TP	Event-related design/between participants – Learning block: 8 min; Entire song: 24 s; One musical phrase: 6 s	Interactive learning of a song through 2 methods: a) phrase by phrase repetition; b) entire song repetition
	Liu et al., 2021	China	Healthy participants – 180 (75 females)/23.1 ± 1.9 – Information on musical education and skills N.R.	**CW-NIRS**: Combination of ETG-4000 (Hitachi Medical Corp., Tokyo, Japan) and LABNIRS (Shimadzu Co., Kyoto, Japan) – 8/0/each participant	MPFC, lTPJ	Block design/ within subject – 250 s	Drumming under three conditions: 1) random drumming (independent drumming without considering others' drumming), 2) coordinated drumming attempting to synchronize with fellow group members, and 3) drumming in sync with metronome
	Rojiani et al., 2018	United Kingdom	Heathy participants – 36 (18 dyads, 19 females)/23.8 ± 3.2 – Musical expertise: 3.1 ± 1.2 on a scale from 1 to 5 (never played to play professionally)	**CW-NIRS**: LABNIRS (Shimadzu Co., Kyoto, Japan) – 42/0	SMG, STG, MTG, TPJ, SMA, PMC, AC	Block design/ within subject – 15 s	Drumming or talking to convey the content of a valenced image. Alternation between "sending" (drumming or talking) and "receiving" (listening) role
	Vanzella et al., 2019	Brazil	Healthy participants – 10 (5 dyads, 5 females)/ 32.7 ± 8.0 – Professional musicians (15 ± 4 years of training)	**CW-NIRS**: NIRScout (NIRx Medical Technologies, LLC., USA) – 23/0	MC, TPJ, SMA, DPFC	Block design/ within subject – 30 s	Playing violin alone or together

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Section	Authors	Country	Sample Characteristics – Number of Participants (n) / Mean Age in years ± SD – Musical education or skills (mean years ± SD)	Type of fNIRS system: model (manufacturer) – Number of channels/ Number of SS channels; Eventual other neuro-imaging/-stimulation tools coupled	Regions of Interest (ROIs)	Study design (block or event related / between or within subjects) – Stimulus duration	Task performed
	Hou et al., 2020	China	Healthy participants – 1 violinist (male)/21 – Formal musical training 16 years Audience: 16 (all females)/20.3 ± 1.9 – Non musicians (no formal musical training)	**CW-NIRS**: ETG-7100 (Hitachi Medical Corporation, Japan) – 22/0	DLPFC, TP	Block design/ within subject – 100 s	Violinist: played musical pieces and was recorded Audience: watching and listening the pre-recorded performance of the violinist
	Sarinasadat et al., 2019	Japan	Healthy participants – 30 (15 dyads, 18 females)/Students (Any other demographic information) – Information on musical education and skills N.R.	**CW-NIRS**: HOT-1000 (Hitachi Medical Corporation, Japan) – 2/0	MPFC	Long blocks/within subject – 6 min	Alternative uses tasks with familiar objects, facilitated by background music of varying valence and genre

including children, adults, the elderly, and patients. The following sections present an overview of the articles included in our review, following a categorization of their main thematic areas within the music cognition research domain: 1) musical activities and expertise, 2) music listening and associated cognitive processes, 3) clinical implications of music and fNIRS, 4) music and development, and 5) music and social cognition.

5.1. *Musical activities and expertise*

Neuroimaging studies investigating musical performance usually require participants to play specially crafted instruments in non-natural postures (e.g., playing the piano or the cello in miniature-adapted versions and lying down in fMRI and PET scanners; Olszewska et al., 2023; Parsons et al., 2005; Wollman et al., 2018). This is often due to the incompatibility of neuroimaging techniques with the physical characteristics of a musical instrument, such as materials (i.e., metallic objects cannot enter the fMRI scanner), shape, dimension, and the kind of artistic gesture required for playing. fNIRS devices enable individuals to potentially play all kinds of instruments without movement constraints and without concerns about material compatibility (Pinti et al., 2018).

fNIRS investigation on music production appeared first with the pioneer study by Hashimoto et al. (2006). Frontal lobe activation was monitored while music students performed two piano pieces with different levels of difficulty and the Keio version of the Wisconsin Card Sorting Test as control task. Results revealed that performing a piano piece with the level of difficulty adapted to the ability of each performer was associated to wider activation of the frontal lobe than when performing an easier piano piece or the control task. fNIRS thus emerges as a potential tool for assessing objectively a maximum level of cognitive workload, useful in defining incremental goals in learning processes or rehabilitation settings (Fishburn et al., 2014). Converging evidence has been reported by Yuksel et al. (2016), who developed an adaptive brain-computer system, named Brain Automated Chorales (BACh). Monitoring the prefrontal cortex (PFC) via fNIRS allowed defining a threshold that corresponds to a maximal cognitive workload in a music learning task. With the assumption that automaticity reduces the demand for cognitive control, BACh integrated this information into the difficulty level of the task: when the PFC activity was below the defined threshold, it automatically increased the difficulty level of the task. Participants who studied a piano piece with this system reported higher accuracy and speed than controls and felt that they had learned better with the support of BACh, showcasing the potential of fNIRS to provide a real-time signal that can be associated with cognitive workload.

These applications reveal the use of fNIRS in the investigation of learning and brain plasticity processes (see e.g. Herholz & Zatorre, 2012), which is particularly promising for the study of motor skill acquisition (Herold et al., 2018; Perrey, 2008). Alves Heinze et al. (2019) investigated the temporal changes in PFC hemodynamic response during a single session of piano training (i.e., learning a chord progression) in individuals without previous experience playing keyboard instruments. fNIRS results revealed an inverted U-shape in the HbO_2 concentration change over task execution, suggesting an initial executive function engagement followed by facilitation of motor task execution over time (but see section 6. *Methodological considerations and recommendations* for a methodological discussion; Brigadoi et al., 2014; Kirlilna et al., 2013).

fNIRS was also used for monitoring the activation of temporal lobes and motor areas during a short-term drum training in non-musicians, notably the execution of a rhythmic auditory cueing task (Curzel et al., 2021). A facilitatory effect of training was reflected in better behavioral performance (measured as beat regularity) and decreased brain activity primarily in premotor areas. Drumming performance (on both acoustic and electronic drums) was monitored with fNIRS for various purposes, in particular for (a) testing rehabilitation protocols, for example for post-stroke patients (Wang et al., 2020), and (b) unveiling the activity of the temporoparietal junction (TPJ) and PFC in dyads or groups playing simple rhythmic movements (Rojiani et al., 2018; Liu et al., 2021; see sections 5.3. *Clinical implications of music and fNIRS* and *5.5. Music and social cognition* for more details). Further studies monitored brain activity with fNIRS for more complex movements, such as a dance simulation gameplay (Ono et al., 2014; Tachibana et al., 2011). Cortical sensory-motor centres were monitored to investigate the processing of sensory inputs (such as visual and rhythmic auditory cues) during coordinated complex movements. Interestingly, an fMRI adaptation of the same procedure confirmed the observed activation pattern in the superior and middle temporal gyri (Noah et al., 2015).

The reduced methodological restrictions of fNIRS also allow for the investigation of real music performance in its complexity, revealing for example decreased left dorsolateral prefrontal cortex (DLPFC) during a guitar playing task including improvisation/creative processes (Tachibana et al., 2019). More recent applications allowed the monitoring of the brain activity of both the player and the audience during a non-simultaneous video-recorded performance (Hou et al., 2020, see section 5.5 *Music and social cognition* for more details).

Some fNIRS studies have investigated cortical activity during singing. Lo et al. (2009) monitored haemodynamic changes of the left inferior motor cortex during word singing versus reading. They additionally coupled fNIRS with transcranial magnetic stimulation (TMS) to study cortical excitability, but only with a small number of participants (n = 5), serving as a potential pilot for future investigations. Further research involved not only singing of a single performer, but also singing with a partner, notably with the communicative and cooperative dimensions of joint singing (Osaka et al., 2015) as well as the interactive learning process of singing a song in dyads composed of a learner and an instructor (Pan et al., 2018a; see section 5.5. *Music and social cognition* for additional details).

As musical training can induce plastic changes in the brain in terms of both grey and white matter (Herholz and Zatorre, 2012; Olszewska et al., 2021; Wan and Schlaug, 2010), music cognition research is interested in the comparison of cognitive performance between non-musicians and musicians (also including participants having acquired some musical expertise in a longitudinal training study), testing differences in neural activations and possible transfer effects of musical training on cognitive functions (see, e.g., Bigand & Tillmann, 2022; Cooper, 2020; Román-Caballero et al., 2022). Daikoku et al. (2012) tracked cortical activation in auditory areas while musicians and non-musicians were listening to consonant and dissonant chord progressions. In musicians, HbO_2 concentration in left auditory areas was higher during the dissonant chord progression compared to the consonant one. No difference was observed in the non-musicians' group, showing again a possible effect of a cortical plasticity derived from musical training. fNIRS was further used to examine the activation of trained musicians' prefrontal cortex in a divergent thinking task (Gibson et al., 2009). Musicians exhibited heightened bilateral frontal activation and enhanced creativity in comparison to non-musicians. Well-trained musicians, compared to a less-trained group, exhibited increased activation of Broca's area in response to the vision of a silent-video showing a hand playing a familiar vs unfamiliar melody on the piano (Wakita, 2014).

Musical imagery, or mentally "playing or replaying or hearing" music, can happen in daily life when recalling a familiar tune, imagining a musical performance or creating new musical ideas in one's mind (Halpern, 2001; Liikkanen and Jakubowski, 2020). This phenomenon has been investigated with different neuroimaging techniques (Herholz et al., 2008), including fNIRS. In particular, musical imagery has been employed in studies aiming at developing a brain-computer interface (BCI). Indeed, some of the fNIRS characteristics, in particular its portability, ease of installation, low cost and silent functioning, make it suitable for its employment as a BCI (Naseer and Hong, 2015). Accordingly, Power et al. (2010) measured and classified prefrontal fNIRS signals evoked by two different cognitive tasks, namely mental arithmetic and music imagery in which participants were instructed to try to feel the emotion elicited by the imagined piece. Based on the fNIRS signal, the two activities were classified with an accuracy of 77.2 % ± 7.0 across participants (Falk et al., 2011; Power et al., 2011, 2012).

Overall, the studies reviewed in this section promote fNIRS as a tool for monitoring cortical activity during musical activities, providing new insights into neural mechanisms involved in music learning, performance, improvisation, interaction, and imagery, including in complex activities, or even involving social interactions (as further developed in section 5.5. *Music and social cognition*).

5.2. *Music listening and associated cognitive processes*

The investigation of brain activation during music listening tasks with fNIRS is particularly advantageous because it operates silently, thus avoiding any potential sound interference. The following sections present a summary of research using fNIRS to monitor cognitive processes related to music listening, ranging from the investigation of perception and affective responses to music to potential implications in other cognitive functions (e.g., memory).

5.2.1. *Music perception and cognitive effects of musical background*

Music represents a complex auditory stimulus, engaging multiple sensory and cognitive processes required for processing key features such as melody, harmony, rhythm, beat, and timbre.

Several studies have investigated cortical responses to the perception of music (with noise or a combination of noise and music as comparison conditions), focusing mainly on the auditory cortex. Santosa et al. (2014) found a progressive effect of lateralization toward the right hemisphere when music was mixed with an increased level of noise, rather than pure noise or pure music. The effect was maximum when the music level was 10–15 % and the noise level 10 % (referring to the audio amplitude scale; the higher level of noise reached 20 %), and it reduced when the noise was higher or lower, probably reflecting participants' efforts in distinguishing the musical content from noise. Subsequent research has demonstrated the possibility of decoding various sound categories (i.e., speech, music, annoying sounds, nature sound, gunshot) using auditory cortex activity assessed via fNIRS (Hong and Santosa, 2016; Yoo et al., 2021). Similarly, a multi-methodological approach combining fNIRS, EEG and behavioural measurements explored how the semantic meaning of spoken or sung sentences was extracted (Rossi et al., 2020). Cortical activation recorded with fNIRS revealed predominant differences in left-hemispheric areas (PFC and temporo-parietal regions) between spoken and sung sentences. Additionally, increased activation was observed for correct sentences compared to incorrect ones (for both spoken and sung modalities) over prefrontal and temporo-parietal regions.

Musical features, such as pitch and timbre, as well as language materials, such as syllables and words, were employed in working memory tests, performed by young non-musicians (Jeong & Ryu, 2016b). Monitoring the PFC during the working memory test execution revealed a significant decrease in neural activity for pitch and timbre musical stimuli compared to syllables and words, and an asymmetry in the nonverbal stimuli (pitch stimuli led to stronger decrease at left PFC, and timbre at right PFC). fNIRS also allowed measuring the cognitive load involved when performing a melodic contour identification task (Jeong et al., 2018a): participants had to identify the direction of a melodic contour (ascending, descending, or stationary) played by different instruments, against auditory distractors presented simultaneously (environmental noises or concurrent melodies). Activity in the frontopolar cortex progressively increased with the increased difficulty of the task, that is when participants had to focus on target melody and suppress the concurrent melodic contour of the distractor, but this increase was not observed when the distractor was noise.

A set of research focused on memory and investigated the influence of music presented in the background during the encoding phase of verbal material on cortical activity and subsequent recall performance. In a study by Ferreri et al. (2013), healthy young adults showed better memory performance for lists of words previously encoded with musical background than in silence. Compared to the silent background, the music condition showed activation during encoding in the left (vs right) hemisphere and sustained, bilateral decrease of activity on the DLPFC, suggesting that music may facilitate episodic memory through the modulation of DLPFC involvement. These findings were replicated in an older adult population (Ferreri et al., 2014b) and when monitoring a larger brain area (i.e., the entire lateral PFC) during both the encoding and the retrieval of verbal material (Ferreri et al., 2015). Taken together, these findings suggested that music-related memory processes are associated with specific cortical prefrontal mechanisms that can be traced through fNIRS.

5.2.2. *Musical affect and its implications in cognitive functions*

The perception and organization of musical features generates expectations and predictions, which are related with pleasure and emotions (Huron, 2006; Salimpoor et al., 2015; Tillmann et al., 2014). Indeed, music listening is often targeted as a means to modulate the perceiver's emotional state (Juslin and Västfjäll, 2008). Neuroscience studies using fMRI and PET allowed revealing neural responses to musical affect not only in deep brain regions, such as the amygdala or the dopaminergic reward circuitry (Koelsch, 2014; Mas-Herrero et al., 2021), but also in other cortical regions, such as the prefrontal, auditory and motor cortices (Koelsch, 2014; Matthews et al., 2020; Putkinen et al., 2021; Salimpoor et al., 2013). This suggests that fNIRS could be a viable tool to investigate neural responses related to perceptual and affective processes associated with music listening in ecological settings, even though it mainly allows investigating the brain with a depth sensitivity of approximately 1.5–2 cm from the surface (Minematsu et al., 2018; Plichta et al., 2011).

Numerous fNIRS studies have monitored the PFC with the aim of characterizing its activation in relation to the emotions felt by participants while listening to either self- or experimenter-selected music (Bigliassi, 2015; Da Silva Ferreira Barreto et al., 2020; Moghimi et al., 2012a). The findings revealed that preferred and motivational music could increase blood flow in the PFC. In a multi-modal investigation combining fNIRS and EEG, Qiu et al. (2022) monitored activity in PFC and temporal lobes induced by listening to one's favorite music. Some studies share the goal of developing a predictive model able to automatically detect participants' feelings and preferences by analyzing the hemodynamic PFC response (Bandara et al., 2018; Moghimi et al., 2012b; Qiu et al., 2022; Yamada & Ono, 2019). Some efforts have been also made to study the potential difference in cortical activation induced by different music styles (Bigliassi et al., 2015a; 2015b; 2015c), also considering gender as a potentially modulating factor (Bigliassi, 2015). Although with some methodological limitations (see section 6. *Methodological considerations and recommendations*), these studies suggest fNIRS as a promising tool for investigating music-driven emotional processes, which also allows potential clinical applications (see section 5.3 *Clinical implications of music and fNIRS*).

Music-driven emotional modulations can play a role in boosting cognitive, social, and motor functions (Chanda & Levitin, 2013; Ferreri & Rodriguez-Fornells, 2022; Fiveash et al., 2023; Fukui & Toyoshima, 2014; Ripollés et al., 2016). A recent study found that listening to groovy (i.e., related to the pleasure and urge to move) music (featuring low-to-medium syncopation levels) boosted activity in the left DLPFC, and enhanced executive functions (i.e., response times in a Stroop task), in particular for participants who felt positively affected and groovy (Fukuie et al., 2022). fNIRS was used to monitor PFC activity related to executive functions (i.e., Stroop task) before and after a pedaling activity with music, notably via its induced positive mood (vs with a metronome; Suwabe et al., 2021). The induction of a positive mood by the music during pedaling led to increased activation in the left DLPFC and improved executive performance (i.e., better results in the Stroop task). Bigliassi et al. (2015c) applied fNIRS to study the effect of music (calming vs motivating with fast tempo and slow tempo vs no music) on brain activity and physiological recovery and combined those measurements with running performance. Pleasurable and motivating music (both with fast and slow tempo) promoted increased activation in the PFC, reduced performance time in a 5 km-run and accelerated physiological recovery in participants. However, this study recorded neural activity only before the physical activity, not during/after it. More evidence and a more reproducible study design would be therefore needed to confirm these neural findings.

Overall, fNIRS has been employed in different paradigms involving music perception, music-induced affective responses, and cognitive performance without experimental constraints. The ability to discriminate sound features and affective responses from cortical signals, together with new advancements in the field of BCI (Naseer et al., 2015), offer promising perspectives for clinical applications.

5.3. *Clinical implications of music and fNIRS*

The rising number of studies conducted in recent years with fNIRS and music, together with the increasingly evolving neuroscience-informed music interventions in clinical populations, (Altenmüller and Schlaug, 2013; Bower et al., 2021; Thaut et al., 2016), are leading to the growing interest for fNIRS and music applications in clinical settings. The main features of fNIRS (summarized in Table 1) place it as an excellent neuroimaging tool for working with special populations, often excluded by limitations or incompatibilities with other neuroimaging tools (Chen et al., 2020; Irani et al., 2007; Rahman et al., 2020). These special populations include patients presenting severe neurologic or psychiatric disorders, preterm babies, newborns, patients with hearing aids or cochlear implants, as well as children and the elderly (Blasi et al., 2011; Li et al., 2023; Saliba et al., 2016; Shatzer & Russo, 2023). Moreover, its non-invasiveness and portability also allow for an easier access to detection, diagnosis, and monitoring of neurological disorders (Ayaz et al., 2022).

The combination of fNIRS and music perception in the clinical domain has been explored for diagnostic purposes. Jeong & Ryu (2016a) monitored the PFC of young and old populations while performing melodic contour identification tasks. Results showed decreased activity in the right dorsolateral PFC in old (versus young) adults, highlighting a possible marker of age-related cognitive decline. The same task has been successfully used to identify a biomarker of auditory attention deficit in patients with acquired brain injury (Jeong et al., 2018b). fNIRS feasibility for diagnostic purposes was also tested in pediatric traumatic brain injury patients, including the monitoring of cognitive task performance, with music listening employed in a resting phase, while patients were in supine position (Da et al., 2021). fNIRS was also used as a potential detector of covert consciousness in clinically unresponsive patients by individuating distinct cortical responses to preferred music listening (in comparison to silence) using a frequency domain approach (Bicciato et al., 2022). The possibility of isolating specific markers of brain activity promotes the use of fNIRS not only for diagnosis and prognosis, but also for BCI clinical applications (see Naseer & Hong, 2015 for a review).

In the clinical domain, fNIRS has been further employed for investigating the potential benefits of music interventions on psychological and psychiatric disorders (such as major depression, Feng et al., 2019) and monitoring their effectiveness in rehabilitation protocols. For example, fNIRS was used to measure hemodynamic changes in prefrontal and motor cortex of stroke patients following different rehabilitation tasks, including music listening (Saitou et al., 2000), rhythmic games (Q. Wang et al., 2020), and the use of musical rehabilitation objects (i.e., a music rehabilitation glove; Li et al., 2020). For adults with mild cognitive impairment, fNIRS was used to measure PFC activation together with cognitive task performance to reveal potential benefits of a 3-month long, weekly multitask movement therapy combined with music (i.e., simultaneously using a percussive instrument, singing, and following instructor's movements) or not (counting aloud and following instructor's movements; Shimizu et al., 2018). After the intervention including music, activation of the medial PFC was increased, functional connectivity in the PFC enhanced, and performance was better in the frontal assessment battery (i.e., a series of 6 tasks used for assessing cognitive performances) compared to the control group.

Musical interventions, and in particular those involving active musical playing, have shown great potential in alleviating symptoms of neurodegenerative pathologies, such as Parkinson's and Alzheimer's diseases (Dalla Bella et al., 2015; Pereira et al., 2019; Raglio et al., 2015; Samson et al., 2009). With its resistance to movement artefacts, fNIRS represents an ideal neuroimaging tool for monitoring rehabilitation protocols that incorporate motor tasks (see section 5.1. *Musical activities and expertise*). However, this potential remains largely unexplored, and possibly constitutes one of the promising future directions in the applications of fNIRS in music cognition and clinical research.

In sum, these studies suggest that fNIRS application in the clinical domain offers a unique opportunity for gaining more knowledge about music-driven effects, in turn opening new perspectives and applications for music-based interventions and neuroscience-informed therapies

(Agres et al., 2021; Chen et al., 2022; Tervaniemi, 2023).

5.4. Music and development

The human fetus develops the capacity to perceive and process sounds prior to birth, typically around 25 weeks of gestational age (Eggermont and Moore, 2012), and the human brain shows the ability to specifically respond to musical stimuli starting the first hours of life (Perani et al., 2010). However, it is not fully understood yet how the newborn brain processes musical features and how they influence cognitive development. This is partly due to the methodological challenges encountered in the study of this special population (i.e., difficulty to control infants' movement, invasiveness, and non-portability of other neuroimaging techniques). Thanks to its features, fNIRS appears as an optimal tool for monitoring premature babies and toddlers (see Table 1; see Gervain et al., 2023 for a review; Wang et al., 2020). Moreover, thin skull and tissues allow light to penetrate deeper in the cortical surface of infants' brains than in the cortical surface of older individuals' brains. While the first attempt to investigate babies' musical brain through fNIRS concerned the frontal activation during music listening (i.e., popular piano music, Sakatani et al., 1999), the main interest then focused on newborn brains' activation comparing music (i.e., popular piano music and chromatic scales played with the piano) and speech (Fava et al., 2014b; Homae et al., 2012; Kotilahti et al., 2010; but see also section 6. *Methodological considerations and recommendations* for possible limitations), highlighting the infant brain's sensitivity to pitch changes in auditory sequences (Homae et al., 2012).

A promising body of research is exploiting fNIRS to study the beneficial effect of music on the preterm brain. In fact, although more research is required to elucidate the mechanisms and customize potential interventions, some studies showed that music interventions in neonatal intensive care units can lead to a reduction of stress and to a closer to at-term newborns neurodevelopment (Lordier et al., 2019; see Anderson & Patel, 2018; Pineda et al., 2017 for reviews). Ren et al. (2021) studied the effects of a short-term music therapy on preterm infants based on classical music listening sessions in the incubators, each containing 12 min of music stimulation, conducted for three consecutive days. Their findings revealed that the preterm brain can perceive different musical features by activating specific brain areas, particularly observing left lateralization in the superior temporal gyrus for timbral, dynamic, and rhythmic musical components. However, a connectivity analysis suggested that the short-term music intervention did not promote a significant change in functional connectivity. Meder et al. (2021) tested the effects of music therapy sessions that included maternal singing accompanied by the guitar of a music therapist and ended with a skin-to-skin care by the mother. Results showed a modest increase of brain activity in temporal regions and a reduced variability in cerebral oxygenation and peripheral oxygen saturation during the musical intervention. Further studies are needed to understand and explore short- and long-term clinical effects of such interventions, and considerations for clinical practice in music therapy should be taken into account (see Bower et al., 2021 for a review). While less developed, there are also interesting findings in the realm of fNIRS and music applications in children populations. Kovelman et al. (2012) used fNIRS to explore the neural mechanisms behind language and reading acquisition in children, focusing on the role of language rhythmic modulations. In particular, children underwent a phonological rhyme awareness task (i.e., listening to pairs of words and detecting the eventual rhyme), a word-match task (i.e., listening to pairs of words and detecting if they were identical), and a rhythm perception task with music-like materials (i.e., listening to a brief beep played at three frequencies: 0.5 Hz, 1.5 Hz and 3.0 Hz). Their findings suggest that the right hemisphere was overall more activated in language and rhythm perception tasks, and that the left hemisphere's activation is more specific to a preferred range of slow frequencies (1.5 Hz).

Overall, the application of fNIRS to study infants and children represents a great opportunity for investigating the early developing brain in ecological contexts with minimal constraints. More specifically, it could open new perspective for investigating the impact of music as a supportive tool for typical cognitive development and provide new insights for understanding the origins and potential role of music in human's life.

5.5. Music and social cognition

Cognitive neuroscience increasingly turns to the study of neural mechanisms within interacting brains. Instead of recording single brains, the "second-person neuroscience" (or "two-body neuroscience") approach aims at recording two or multiple brains during social interaction and emotional engagement with others (Dumas, 2011; Redcay and Schilbach, 2019). The development of this new approach has been, in part, possible thanks to the technological advancements in brain imaging methods, enabling the simultaneous recording of hemodynamic and neuroelectric activity of multiple brains (Babiloni and Astolfi, 2014), also known as "hyperscanning" (Montague et al., 2002). Although still a relatively recent research domain, much effort has been put in the development of the investigation of how human brains tend to align in social situations (Gvirts and Perlmutter, 2020). As a portable and silent tool that allows participants to move, fNIRS is an ideal method for studying close-to-real interactions between individuals (see Table 1; Pinti et al., 2020).

Music is an intrinsically social stimulus able to promote social bonds and synchronization across large groups of individuals (Koelsch, 2013; Nummenmaa et al., 2021; Savage et al., 2021; Tarr et al., 2014). Music represents one of the earliest and most accessible forms of interpersonal interaction, universally used for engaging infants through songs and rhythmic movements (Nguyen et al., 2023; Trehub, 2019). Music production involving multiple musicians, which inherently requires synchronization, represents an ideal way to investigate human interactions and cooperation in an ecological setting (Acquadro et al., 2016). fNIRS hyperscanning allows the investigation of neural mechanisms underlying cooperative singing, revealing increased neural synchronization in the left inferior frontal cortex compared to singing alone, regardless of whether participants were facing each other or not (Osaka et al., 2015). fNIRS also allows monitoring Inter-personal Neural Synchrony (INS) during the interactive social learning of a song, revealing the synchronization between learner and instructor in the bilateral inferior frontal cortex, in particular for active interactions. Interestingly, the recorded synchronization predicted also the learner's behavioral performance (Pan et al., 2018). In a study involving groups of nine participants, INS was assessed during drumming activity under three conditions: random drumming (i.e., independent drumming without considering others' drumming), coordinated drumming in an attempt to synchronize with fellow group members, and drumming in synchrony with a metronome (Liu et al., 2021). The monitoring of fronto-temporal brain regions revealed that when participants endeavored to synchronize their beats with others (i.e., coordinated drumming), the highest level of neural synchrony was observed in their left TPJ and medial PFC. Drumming was also studied as a means of emotional communication in dyads (Rojiani et al., 2018) where participants facing each other had to convey the emotional content of valenced and arousing images through either drumming or verbal communication. Results showed that the drumming condition elicited greater activation in the right temporo-parietal junction than did the talking condition in the listener (in each participant in turn).

fNIRS reliability in a naturalistic environment has been further shown in studies investigating violinists' performance. Measuring two violinists playing together revealed that the roles of leader and follower engaged distinct patterns of functional brain activation, with greater involvement of temporo-parietal and somatomotor regions for the follower of the duo than for the leader (Vanzella et al., 2019). The INS between a violinist (with pre-recorded video and neural activity) and the audience was explored while assessing the audience ratings of their liking for the performance (Hou et al., 2020). The popularity of the performance correlated positively with the INS in the left temporal cortex between violinist and participants watching the video performance, suggesting a potential role of INS in this area in music appreciation.

Sarinasadat et al. (2019) explored the impact of music valence and genre on creativity tasks and inter-personal synchrony (i.e., inter-neural and head-movement synchrony) within dyads of participants. Music, in contrast to silence, led to higher head-movements synchrony but did not modulate INS (in two channels placed over the PFC) between participants. Behavioural findings revealed that the exposition to upbeat and positively valenced music promoted increased dyads creativity and heightened mutual engagement.

In sum, the various application of fNIRS confirms it as an ideal method for musical paradigms studying social interactions in ecological situations. In particular, fNIRS allows the investigation of cortical activity during music playing, singing, communication, affective experiences, music learning, and cooperative tasks in social situations, emphasizing a social, inter-brain perspective rather than solely an individual brain-focused approach. Even though still in its early stages, this approach constitutes a fundamental step towards the understanding of the neural basis of social phenomena in real-world scenarios.

6. Methodological considerations and recommendations

The here-reviewed research suggests fNIRS as an efficient and reliable tool suitable for diverse environments, various populations, and relatively easy to use, which is spreading worldwide ("fNIRS and music word map"https://gxhorp-federicocurzel.shinyapps.io/musicfNIRSmap/[2]:; Ayaz et al., 2022; Cutini & Brigadoi, 2014; Gervain et al., 2023; Piper et al., 2014). Considering the rising number of studies in this area, and the fact that fNIRS is a relatively recent neuroimaging tool, it is fundamental to acknowledge potential methodological criticisms and follow solid and reproducible experimental procedures. Recent works comparing different approaches outline the best practices in fNIRS use (Brigadoi et al., 2014; Di Lorenzo et al., 2019; Tak & Ye, 2014; Yücel et al., 2021) aiming to reduce methodological weaknesses (see e.g. Herold et al., 2018). The next section will (1) highlight intrinsic technical limitations of fNIRS, along with the most recent solutions to overcome them, and (2) propose some methodological guidelines for fNIRS studies investigating music processing, notably concerning design, paradigm, data collection and analyses.

6.1. *fNIRS intrinsic limitations and how to deal with them*

Although fNIRS overcomes several limitations of other neuroimaging techniques (see Table 1), it also presents some intrinsic limitations that should be borne in mind when conducting fNIRS research and when interpreting the results (including the studies presented here).

(1) Due to a limited penetration depth of light, fNIRS enables monitoring only the cortical surface of the brain (Pinti et al., 2020; Scarapicchia et al., 2017). fNIRS measurements exhibit high sensitivity to scalp and skull tissues and to the associated blood vessels activity. Light might also be attenuated by dark and curly hair and by high concentrations of melatonin, thus avoiding preferentially the inclusion of participants with dark skin (Kwasa et al., 2023). Even though efforts must still be made towards the diversification of the studied populations (Doherty et al., 2023), new generation fNIRS devices allow overcoming, at least partially, participant exclusion due to skin or hair color, thus suggesting solid technological solutions for signal optimization in the near future (Lloyd-Fox et al., 2017; Perdue et al., 2019; Wijeakumar et al., 2019). To isolate extracortical-related hemodynamics, optode arrays should include 'short-separation' channels (Gagnon et al., 2011). These channels are shorter, approximately 1 cm in length, with light penetrating only the external tissues (see *Basic Principles of fNIRS* section; Fig. 1). Consequently, regressing the signal recorded by short-separation channels from the signal recorded by standard channels (~3 cm), allows removing extracortical physiological noise. The accuracy of the cortical signal, therefore, is improved with the inclusion of more short-separation channels across the monitored brain area (Brigadoi & Cooper, 2015).

(2) In comparison to other neuroimaging techniques, such as fMRI, another limitation of fNIRS concerns its relatively poor spatial resolution (Cui et al., 2011). This limitation can be at least partially overcome by recent procedures, such as the spatial registration of optodes following standardized procedures, the use of digitizers (Singh et al., 2005; Tsuzuki et al., 2007), participants' MRI structural model (Aasted et al., 2015; Tsuzuki and Dan, 2014), and more recently through smartphone-based photogrammetry (Mazzonetto et al., 2022). Nevertheless, the spatial resolution of continuous-wave devices is restricted from 1 to 3 cm (i.e., length of a measurement channel). Specific, relatively recent, fNIRS systems allow obtaining higher spatial resolution, but they are more expensive and less portable than fNIRS continuous-wave devices. For example, High-Density Diffuse Optical Tomography are fNIRS systems with a higher density of optodes positioned on the scalp creating a thick network of channels with various lengths, overcoming intrinsic limitations due to channel lengths (Eggebrecht et al., 2014). Furthermore, tomographic algorithms applied to the signal collected by these systems allow reconstructing a precise 3D image of brain activation, close to fMRI data reconstruction (Ferradal et al., 2014).

(3) The relative newness of fNIRS technology might explain the current lack of standardized procedures for signal processing and data analysis that decrease the comparability and reproducibility of the results (Di Lorenzo et al., 2019; Herold et al., 2018; Yücel et al., 2021). This becomes particularly relevant in music cognition research, where the flexibility of the instrument together with its ecological validity have led to multiple investigations across a wide variety of experimental settings in different populations (see Table 2).

6.2. *fNIRS and music: Methodological caveats*

Several studies included in this review are subject to important methodological criticisms, such as small sample sizes (21.7 % of studies included less than 10 participants), missing information regarding participants (e.g., not specifying the level of musical expertise), insufficiently detailed or missing technical specifications (e.g., concerning the precise optode location information or the presence/absence of short-separation channels), weak paradigm designs (e.g., not including sufficiently long resting periods), and inaccuracies or omissions of information related to the pre-processing of the fNIRS signal (e.g., signal quality assessment, motion correction techniques). Another important aspect to report is the absence of short-separation channels in nearly all the works included in this review (except for two; see Table 2 for further details). This could have an impact on the quality of the measured signals and reported results, as they could embed traces of physiological noise (for the employment of short-separation channels see the section 6.2.3. *Processing and analyzing fNIRS data*; Gagnon et al., 2011).

In the following sections, we will present general caveats and advice for fNIRS studies, along with specific examples for music cognition applications, offering guidelines of good practices for future research.

6.2.1. *Choice of brain areas and optode placement*

As numerous fNIRS devices are not covering the entire scalp (i.e., they are not full-head systems), specific brain regions need to be

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[2] A continually updated map, featuring both past and upcoming work involving fNIRS and music, is provided alongside with this review. Authors reading this work who may be interested in including their studies meeting the inclusion criteria outlined in section 3.2 are invited to submit key information by following the instructions provided on this webpage.

selected. As reviewed in sections 5.1 to 5.5, numerous brain areas are relevant for the study of music cognition, as also shown in Fig. 3 (see also Table 2 for specific information about each study).

For fNIRS recording, it is necessary to follow standardized procedures for optode placement as the technique itself does not provide information about anatomical locations. Various toolboxes are available to support the creation of the best optodes' configuration covering the region of interest, such as "Array Designer" (Brigadoi et al., 2018), "Optodes Location Decider (fOLD)" (Zimeo Morais et al., 2018), and "devfOLD" (Fu and Richards, 2021). These toolboxes ensure the best anatomical specificity and sensitivity, which can be further tested through the "AtlasViewer" toolbox (Aasted et al., 2015). The distance between an emitter and a detector should be between 3 – 4 cm for adults and 2 – 2.5 cm in infants, allowing for optimizing light penetration depth and limit attenuation (Patil et al., 2011; Pinti et al., 2020). Given that numerous fNIRS studies investigating music processing monitor hemodynamic responses in the PFC, it is important to also consider that the prefrontal blood vessels oxygenation can hinder observing the actual cortical hemodynamic signals (Kirlilna et al., 2013). Accordingly, optode placements should try to avoid the overlap of channels with big blood vessel positions, and the sensitivity of their placement should be tested on virtual brain models (Aasted et al., 2015). The use of short-separation channels is highly recommended: the more numerous and the better distributed they are, the better the neural signal can be isolated from the physiological noise (Yücel et al., 2015). It should also be taken into account that optodes positioned in the lower frontal area could embed significant motion artefacts due to eyebrow movements, particularly when monitoring social interactions (Balardin et al., 2017a; 2017b). A primary factor contributing to artifact generation is often related to the fitting of the cap. This procedure must be conducted attentively by ensuring proper hairs placement (i.e., not obstructing the passage of light through the optodes), stabilizing optodes and cables, and checking the signal before recording. Accordingly, it has been shown that minor head movements such as nodding have minimal impact on signal quality with a properly fitted cap (Balardin et al., 2017a; 2017b).

6.2.2. Paradigm design

In fNIRS studies, including those investigating music cognition, block designs stand out as the most common paradigms, followed by event-related designs (Yücel et al., 2021; see Table 2).

When designing an fNIRS experiment, numerous methodological issues need to be considered; some being similar to constraints in fMRI. Repeating the stimulus multiple times allows for reducing the probability to embed physiological confounds in the recorded signal (Klein et al., 2022b) and increases the probability to effectively isolate the neural response to a stimulus (Amaro and Barker, 2006). To avoid a confounding effect that may be caused by the aligning with physiological pattern frequencies (e.g., respiration, heart rate, "Meyer waves" originating from blood pressure; Kirlilna et al., 2013), it is necessary to introduce pseudo-random, jittered intervals between successively presented stimuli. In addition, adequate baseline durations between stimuli (i.e., resting periods with a similar length to the stimulation period) are needed to contrast activation periods (Amaro and Barker, 2006; Herold et al., 2018).

Designing experimental paradigms involving music is challenging due to the inherent complexity of the musical stimulus, characterized by diverse sound features, attributes, and temporal dynamics likely to

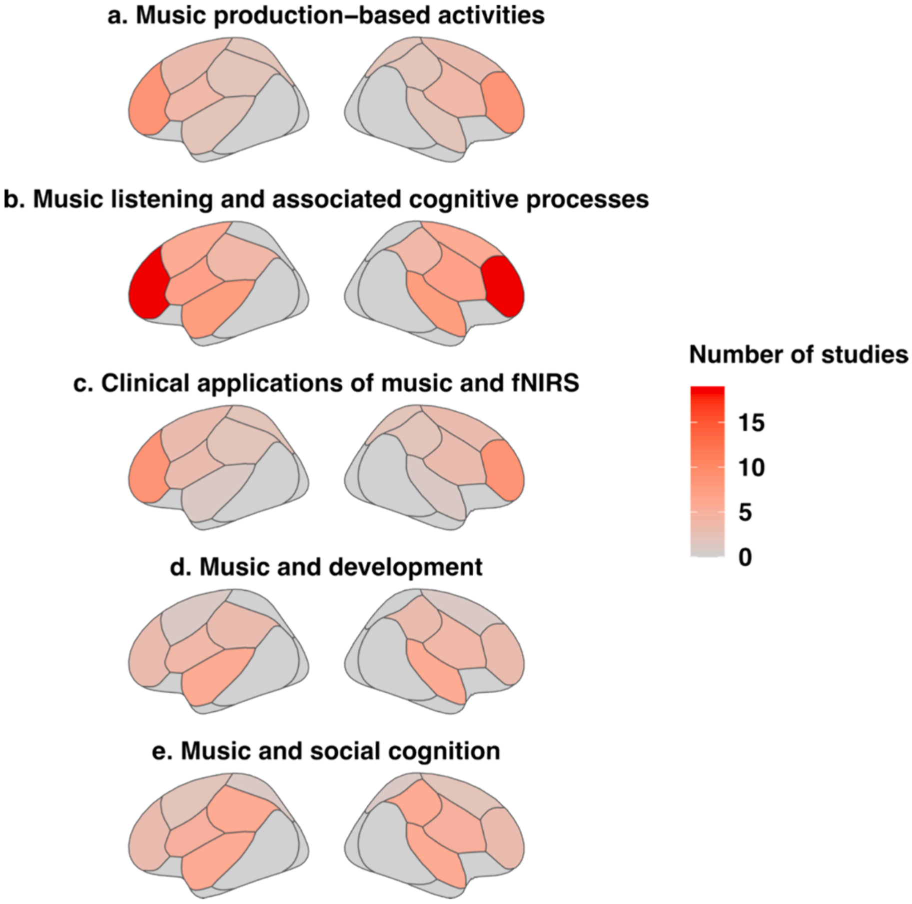

Fig. 3. Brain areas monitored in the reviewed papers grouped by topic (see section 5. fNIRS and music cognition). The number of studies is represented in the different shadows of red. This figure was generated through the R package "ggseg" (version 1.6.6; Mowinckel & Vidal-Piñeiro, 2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

modulate both hemodynamic and physiological parameters (e.g., heart beat influenced by music tempo; Kulinski et al., 2022). Furthermore, when implementing fNIRS block designs, presenting the same musical stimulus over time may not always be a viable option. For example, in studies investigating musical emotion or memory, the repetition of the same excerpts might hinder or interfere with the behavioral and emotional responses (e.g., influencing memory performance or the pleasure felt by participants; Ferreri et al., 2019; Mas-Herrero et al., 2018). In such cases, achieving a balanced selection of different music excerpts becomes a delicate endeavor and requires the extraction and consideration of various musical attributes (e.g. valence, arousal, familiarity, etc.).

Beyond these most often used paradigm structures that are based on multiple items or repetitions of short stimuli, other more complex designs with longer stimuli are also employed (e.g., resting-state, without simulation, Bulgarelli et al., 2019; hyperscanning, Nguyen et al., 2021; naturalistic scenarios, without triggers, Da Silva Ferreira Barreto et al., 2020).

6.2.3. *Processing and analyzing fNIRS data*

Only a limited number of the studies included in this review systematically report the procedure applied to raw signal processing. This may be attributed to inconsistencies about fNIRS processing protocols within the past literature. Nowadays, an increasing number of guidelines have been proposed aiming to converge on most robust and appropriate methodologies (Di Lorenzo et al., 2019; Gemignani et al., 2023; Hocke et al., 2018; Nguyen et al., 2021; Orihuela-Espina et al., 2010; Pinti et al., 2019; Tachtsidis and Scholkmann, 2016; Yücel et al., 2021). In this context, dissemination and promotion of good research practices have been proposed by the Society for Functional Near-Infrared Spectroscopy (https://fnirs.org[3]), an active and dynamic community of researchers dedicated to advancing the field of fNIRS.

Several open-source toolboxes with implemented functions for the processing and analysis of the signal are available, such as “Homer3” (Huppert et al., 2009) and “MNE-NIRS” (Gramfort, 2013; Luke et al., 2021), among others (see also Fekete et al., 2011; Hou et al., 2021; Montero-Hernandez & Pollonini, 2023; Muccigrosso et al., 2018; Santosa et al., 2018; Sutoko et al., 2016; Tadel et al., 2011; Xu et al., 2015; Ye et al., 2009). In the following we provide an overview of the most relevant analyses steps, combined from various sources, along with our suggestions for their practical implementation.

Preprocessing. Regardless of the employed toolbox, signal processing must contain some elementary steps that should be reported (Pinti et al., 2019; Yücel et al., 2021).

1) The quality of the signal is assessed, notably by checking the signal-to-noise ratio, by obtaining cardiac power at each channel through spectral analysis, or by using a toolbox that provides a composite quality value (“QT-NIRS”, Montero-Hernandez & Pollonini, 2023; Pinti et al., 2019; Pollonini et al., 2016). Channels with recorded signals that are characterized by low quality and excessive noise are rejected. This can be assessed through visual inspection of the signal (i.e., the ability to detect the heart rate in the signal), and by applying specific thresholds (e.g., as defined in studies like Bonilauri et al., 2021, and depending on the specific toolbox or parameters used; Montero-Hernandez & Pollonini, 2023; Yücel et al., 2021).
2) The signal is then converted through a logarithmic transformation from intensity (i.e., the ratio of transmitted to incident light intensity) to optical density. Optical density is a derived measure that characterizes the attenuation of light through the tissue.
3) Subsequently, motion-related artifacts are corrected using specific techniques (Yücel et al., 2021). This is particularly relevant in music cognition design when musical activities (e.g., playing music, dancing) are intrinsically related to motor processes (Janata et al., 2012; Thompson and Luck, 2012). Various methods are available (e.g., Temporal Derivative Distribution Repair, Fishburn et al., 2019), and the choice depends on the nature of the signal artifacts (Brigadoi et al., 2014; Di Lorenzo et al., 2019).
4) The extracerebral and physiological noise (e.g., cardiac pulsation, respiration frequency) should then be removed via the regression of the signal recorded with short-separation channels (Brigadoi and Cooper, 2015; Klein et al., 2022b) and digital filtering of the signal, respectively.
5) Changes in optical density are then converted into changes in the concentration of HbO_2 and HbR (Baker et al., 2014; Delpy et al., 1988, 1997).[4]
6) As the last step of the signal processing, the hemodynamic response function (HRF) is estimated using block averaging, convolution, or linear estimation models.

Analysis. The general linear model (GLM) is one of the most common approaches used in the fNIRS community, similar to fMRI data analyses (Poline and Brett, 2012). GLM can take advantage of the high temporal resolution of fNIRS and employ various regressors to improve the inference accuracy (Gagnon et al., 2011; Huppert, 2016; Pinti et al., 2019; Tachtsidis & Scholkmann, 2016; Tak & Ye, 2014). To enhance the robustness of the signal and analysis, it is advisable to aggregate channels in regions of interest (Bulgarelli et al., 2019). The choice of the subsequent statistical tests depend on the design of the study and the hypothesis, but tests should be corrected for multiple comparisons (Plichta et al., 2006; Singh & Dan, 2006). As a general consideration in processing fNIRS signals, it is crucial to strike a balance between preserving authentic neural activity and minimizing noise. It is recommended to report the results in terms of variations in the concentrations of HbO_2 and HbR, as both can provide information about the hemodynamic response and help detect any residual systemic confounding effects after preprocessing (Tachtsidis & Scholkmann, 2016). However, various practices for reporting results can be found in the literature, including combinations of the two chromophores (either the total concentration or the difference in concentration between HbO_2 and HbR) or only one of the two (Kinder et al., 2022). The most common practice is to report HbO_2 only, as HbO_2 is positively correlated with the fMRI BOLD response and shows larger signal-to-noise ratio and amplitude as compared to HbR (Kinder et al., 2022). The results of the preprocessing and analysis of the fNIRS signal can also be projected virtually onto digital models of the brain, that could be the MRI reconstructed structure of a single participant or brain atlases (Aasted et al., 2015; Luke et al., 2021; Muccigrosso et al., 2018; Tadel et al., 2011; Ye et al., 2009).

Subsequently, more sophisticated analysis can also be performed, in particular in hyperscanning settings where signals are recorded from more than one NIRS system at the same time. In this case, the aim of the analysis is to determine the degree of synchrony between two or more brain signals (Montague et al., 2002). As reported in section 5.5. *Music and social cognition*, hyperscanning is one of the most interesting and potentially impactful applications of fNIRS in the music cognition domain. Some guidelines and toolboxes have been recently developed for conducting this kind of analysis (Ayrolles et al., 2021; Gvirts Problovski et al., 2023; Lee et al., 2023; Nguyen et al., 2021). Up to now, Wavelet Transform Coherence seems the mostly used method to obtain

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[3] The website of the Society for Functional Near-Infrared Spectroscopy represents an important reference for learning, news in the domain, and resources (e.g., a list of software for data analysis: https://fnirs.org/resources/data-analysis/software/).

[4] Note that in continuous-wave fNIRS systems, the mean pathlength of light from the emitter to the detector (or differential pathlength factor, DPF) is not known. Therefore, in absence of time-domain or frequency-domain fNIRS systems which are capable of measuring it, it must be sourced from standard values in the literature and reported in the publication (Delpy et al., 1988).

INS values, more specifically by the cross-correlation of two time series as a function of frequency and time (Czeszumski et al., 2020; Zhang et al., 2020). New developments, accompanied by joint efforts to document and standardize signal processing steps (e.g., Yücel et al., 2021, among others), as well as the increased adherence to open science protocols and the sharing of toolboxes, will likely result in more easily implementable pipelines soon.

A similar analytical approach to the one used for hyperscanning could be employed to evaluate neural interactions among distinct brain regions, also referred to as functional and effective connectivity (Bulgarelli et al., 2019; Duan et al., 2012; Lu et al., 2010; toolboxes: Xu et al., 2015; Ye et al., 2009). Functional connectivity refers to the statistical association between different signal time series (single channels or, more strongly recommended, regions of interest) and measures their correlation or coherence (Tak & Ye, 2014). It could be implemented as a seed-based approach in which a "seed" channel or region is selected as a reference point for all correlations. Alternatively, in a network approach (also known as graph analysis) various properties of the nodes (channels or regions) and edges (functional connections) composing the brain network are quantified, providing a more holistic view of the brain's functional organization (Novi et al., 2016; Tak & Ye, 2014). Effective connectivity refers to inferring a causal influence or directionality of the connections between channels or brain regions, and is usually assessed with dynamic causal modelling (Bulgarelli et al., 2018; Tak et al., 2015). In the music cognition domain, functional and effective connectivity analyses are particularly relevant for monitoring potential changes in the networking of the brain regions involved in musical activities, which could serve as an indicator of learning as well as developmental and pathological processes.

Future extensions could come from the application of machine-learning to fNIRS data (Eastmond et al., 2022), which could serve to classify specific neural activation patterns (Emberson et al., 2017; Fernandez Rojas et al., 2019; see possible applications in section 5.3. *Clinical implications of music and fNIRS*) or to optimize some steps in the processing of the signal (e.g., artifacts detection and correction).

7. Conclusion and future directions

Over the last years, the interest in fNIRS and music research has been rapidly growing all over the world (https://gxhorp-federicocurzel.shinyapps.io/musicfNIRSmap/). In this review article, the main studies employing fNIRS in the domain of music cognition are presented, highlighting their strengths and limitations, as well as potential solutions and guidelines to reach rigorous applications. The relatively recent entrance of fNIRS in cognitive neuroscience research poses certain challenges when studying the variety of cognitive processes related to music perception and production, but also fuels the drive for new discoveries and technological advancements in fundamental, developmental, and clinical research. Future applications of fNIRS in the field of music cognition are promising, overcoming technical limitations of other neuroimaging tools. The fact that it is silent and it can be coupled with other neuroimaging methods (e.g., EEG or neurostimulation tools) will further allow testing central questions of music cognition, such as those related to music perception (e.g., Koelsch, 2011; Särkämö et al., 2013; Vuust et al., 2022; Zatorre et al., 2007, 2013), music memory (e.g., Peretz et al., 2009; Platel et al., 2003) or investigate parallels with language cognition (e.g., Albouy et al., 2019; Gordon et al., 2011; Heard & Lee, 2020). Furthermore, it could allow testing under more ecological conditions and extending the investigation to participants difficult to test with other neuroimaging techniques because of their technical demands (e.g., toddlers, patients with behavioral, neurological, and psychiatric disorders, individuals with hearing aids or cochlear implants). Given its rapid technical advances and accessibility, fNIRS should soon be a reliable tool to be used also in clinical settings (Eggebrecht et al., 2012; Zinos et al., 2024), providing the possibility of monitoring the neural correlates of music processing as a therapeutic, preventive, or diagnostic means. The affordability of the tool will also facilitate widespread use in different countries (as suggested by the *music and fNIRS world map* included in this review) and encourage cross-cultural studies. Advancements in portable and wireless fNIRS technology will increasingly enable the investigation of music cognition in real-world settings. This includes exploring the social nature of music and elucidating its role in social interaction and communication (Izen et al., 2023). Simultaneously measuring brain activity in multiple individuals engaged in musical activities will provide a deeper understanding of how music facilitates social bonding and interpersonal synchrony (e.g., Fiveash et al., 2023; Nguyen et al., 2023; Savage et al., 2021). In sum, future research directions using fNIRS align with current priorities of investigations in the music cognition domain: the need to review and update models of music perception and production in ecological conditions with more inclusive and cross-cultural studies, and to study how music shapes social interactions and shared meanings (Tervaniemi, 2023; Vuust et al., 2022).

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CRediT authorship contribution statement

Federico Curzel: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Barbara Tillmann:** Writing – review & editing, Validation, Supervision, Conceptualization. **Laura Ferreri:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data are accessible in the body of the article.

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References

Aasted, C. M., Yücel, M. A., Cooper, R. J., Dubb, J., Tsuzuki, D., Becerra, L., Petkov, M. P., Borsook, D., Dan, I., & Boas, D. A. (2015). Anatomical guidance for functional near-infrared spectroscopy: AtlasViewer tutorial. *Neurophotonics, 2*(2), Article 020801. https://doi.org/10.1117/1.NPh.2.2.020801

Acquadro, M. A. S., Congedo, M., & De Riddeer, D. (2016). Music Performance As an Experimental Approach to Hyperscanning Studies. *Frontiers in Human Neuroscience, 10*. https://www.frontiersin.org/articles/10.3389/fnhum.2016.00242.

Agres, K. R., Schaefer, R. S., Volk, A., van Hooren, S., Holzapfel, A., Dalla Bella, S., Müller, M., de Witte, M., Herremans, D., Ramirez Melendez, R., Neerincx, M., Ruiz, S., Meredith, D., Dimitriadis, T., & Magee, W. L. (2021). Music, Computing, and Health: A Roadmap for the Current and Future Roles of Music Technology for Health Care and Well-Being. *Music & Science, 4*. https://doi.org/10.1177/2059204321997709, 2059204321997709.

Albouy, P., Peretz, I., Bermudez, P., Zatorre, R. J., Tillmann, B., & Caclin, A. (2019). Specialized neural dynamics for verbal and tonal memory: fMRI evidence in congenital amusia. *Human Brain Mapping, 40*(3), 855–867. https://doi.org/10.1002/hbm.24416

Altenmüller, E., & Schlaug, G. (2013). Neurologic music therapy: The beneficial effects of music making on neurorehabilitation. *Acoustical Science and Technology, 34*(1), 5–12. https://doi.org/10.1250/ast.34.5

Alves Heinze, R., Vanzella, P., Zimeo Morais, G. A., & Sato, J. R. (2019). Hand motor learning in a musical context and prefrontal cortex hemodynamic response: A functional near-infrared spectroscopy (fNIRS) study. *Cognitive Processing 2019 20:4, 20*(4), 507–513. doi: 10.1007/S10339-019-00925-Y.

Amaro, E., & Barker, G. J. (2006). Study design in fMRI: Basic principles. *Brain and Cognition, 60*(3), 220–232. https://doi.org/10.1016/j.bandc.2005.11.009

Anderson, D. E., & Patel, A. D. (2018). Infants born preterm, stress, and neurodevelopment in the neonatal intensive care unit: Might music have an impact? *Developmental Medicine & Child Neurology, 60*(3), 256–266. https://doi.org/10.1111/dmcn.13663

Anwar, A. R., Muthalib, M., Perrey, S., Galka, A., Granert, O., Wolff, S., Heute, U., Deuschl, G., Raethjen, J., & Muthuraman, M. (2016). Effective Connectivity of Cortical Sensorimotor Networks During Finger Movement Tasks: A Simultaneous fNIRS, fMRI. *EEG Study. Brain Topography, 29*(5), 645–660. https://doi.org/10.1007/s10548-016-0507-1

Ayaz, H., Baker, W. B., Blaney, G., Boas, D. A., Bortfeld, H., Brady, K., Brake, J., Brigadoi, S., Buckley, E. M., Carp, S. A., Cooper, R. J., Cowdrick, K. R., Culver, J. P., Dan, I., Dehghani, H., Devor, A., Durduran, T., Eggebrecht, A. T., Emberson, L. L., & Zhou, W. (2022). Optical imaging and spectroscopy for the study of the human brain: Status report. *Neurophotonics, 9*(S2), S24001. https://doi.org/10.1117/1.NPh.9.S2.S24001

Ayrolles, A., Brun, F., Chen, P., Djalovski, A., Beauxis, Y., Delorme, R., Bourgeron, T., Dikker, S., & Dumas, G. (2021). HyPyP: A Hyperscanning Python Pipeline for inter-brain connectivity analysis. *Social Cognitive and Affective Neuroscience, 16*(1–2), 72–83. https://doi.org/10.1093/scan/nsaa141

Babiloni, F., & Astolfi, L. (2014). Social neuroscience and hyperscanning techniques: Past, present and future. *Neuroscience & Biobehavioral Reviews, 44*, 76–93. https://doi.org/10.1016/j.neubiorev.2012.07.006

Baker, W. B., Parthasarathy, A. B., Busch, D. R., Mesquita, R. C., Greenberg, J. H., & Yodh, A. G. (2014). Modified Beer-Lambert law for blood flow. *Biomedical Optics Express, 5*(11), 4053–4075. https://doi.org/10.1364/BOE.5.004053

Balardin, J. B., Morais, G. A. Z., Furucho, R. A., Trambaiolli, L. R., & Sato, J. R. (2017a). Impact of communicative head movements on the quality of functional near-infrared spectroscopy signals: Negligible effects for affirmative and negative gestures and consistent artifacts related to raising eyebrows. *Journal of Biomedical Optics, 22*(4), Article 046010. https://doi.org/10.1117/1.JBO.22.4.046010

Balardin, J. B., Zimeo Morais, G. A., Furucho, R. A., Trambaiolli, L., Vanzella, P., Biazoli, C., & Sato, J. R. (2017b). Imaging Brain Function with Functional Near-Infrared Spectroscopy in Unconstrained Environments. *Frontiers in Human Neuroscience, 11*, 258. https://doi.org/10.3389/fnhum.2017.00258

Bandara, D., Velipasalar, S., Bratt, S., & Hirshfield, L. (2018). Building predictive models of emotion with functional near-infrared spectroscopy. *International Journal of Human-Computer Studies, 110*, 75–85. https://doi.org/10.1016/J.IJHCS.2017.10.001

Bicciato, G., Keller, E., Wolf, M., Brandi, G., Schulthess, S., Friedl, S. G., Willms, J. F., & Narula, G. (2022). Increase in Low-Frequency Oscillations in fNIRS as Cerebral Response to Auditory Stimulation with Familiar Music. *Brain Sciences, 12*(1), Article 1. https://doi.org/10.3390/brainsci12010042

Bigand, E., & Tillmann, B. (2022). Near and far transfer: Is music special? *Memory & Cognition, 50*(2), 339–347. https://doi.org/10.3758/s13421-021-01226-6

Bigliassi, M. (2015). Music and cortical blood flow: A functional near-infrared spectroscopy (fNIRS) study. *Psychology & Neuroscience, 7*(4), 545. https://doi.org/10.3922/J.PSNS.2014.4.13

Bigliassi, M., Barreto-Silva, V., Altimari, L. R., Vandoni, M., Codrons, E., & Buzzachera, C. F. (2015a). How Motivational and Calm Music May Affect the Prefrontal Cortex Area and Emotional Responses: A Functional Near-Infrared Spectroscopy (fNIRS) Study. *Http://Dx.Doi.Org/10.2466/27.24.PMS.120v12x5, 120*(1), 202–218. https://doi.org/10.2466/27.24.PMS.120V12X5

Bigliassi, M., León-Domínguez, U., & Altimari, L. R. (2015b). How does the prefrontal cortex "listen" to classical and techno music? A functional near-infrared spectroscopy (fNIRS) study. *Psychology and Neuroscience, 8*(2), 246–256. https://doi.org/10.1037/H0101064

Bigliassi, M., León-Domínguez, U., Buzzachera, C. F., Barreto-Silva, V., & Altimari, L. R. (2015c). How does music aid 5 km of running? *Journal of Strength and Conditioning Research, 29*(2), 305–314. https://doi.org/10.1519/JSC.0000000000000627

Blasi, A., Mercure, E., Lloyd-Fox, S., Thomson, A., Brammer, M., Sauter, D., Deeley, Q., Barker, G. J., Renvall, V., Deoni, S., Gasston, D., Williams, S. C. R., Johnson, M. H., Simmons, A., & Murphy, D. G. M. (2011). Early Specialization for Voice and Emotion Processing in the Infant Brain. *Current Biology, 21*(14), 1220–1224. https://doi.org/10.1016/J.CUB.2011.06.009

Bonilauri, A., Sangiuliano Intra, F., Baselli, G., & Baglio, F. (2021). Assessment of fNIRS Signal Processing Pipelines: Towards Clinical Applications. *Applied Sciences, 12*(1), 316. https://doi.org/10.3390/app12010316

Bower, J., Magee, W. L., Catroppa, C., & Baker, F. A. (2021). The Neurophysiological Processing of Music in Children: A Systematic Review With Narrative Synthesis and Considerations for Clinical Practice in Music Therapy. *Frontiers in Psychology, 12*. https://www.frontiersin.org/articles/10.3389/fpsyg.2021.615209.

Brigadoi, S., Ceccherini, L., Cutini, S., Scarpa, F., Scatturin, P., Selb, J., Gagnon, L., Boas, D. A., & Cooper, R. J. (2014). Motion artifacts in functional near-infrared spectroscopy: A comparison of motion correction techniques applied to real cognitive data. *NeuroImage, 85*, 181–191. https://doi.org/10.1016/j.neuroimage.2013.04.082

Brigadoi, S., & Cooper, R. J. (2015). How short is short? Optimum source-detector distance for short-separation channels in functional near-infrared spectroscopy. *Neurophotonics, 2*(2), Article 025005. https://doi.org/10.1117/1.NPh.2.2.025005

Brigadoi, S., Salvagnin, D., Fischetti, M., & Cooper, R. J. (2018). Array Designer: Automated optimized array design for functional near-infrared spectroscopy. *Neurophotonics, 5*(03), 1. https://doi.org/10.1117/1.NPh.5.3.035010

Bulgarelli, C., Blasi, A., Arridge, S., Powell, S., De Klerk, C. C. J. M., Southgate, V., Brigadoi, S., Penny, W., Tak, S., & Hamilton, A. (2018). Dynamic causal modelling on infant fNIRS data: A validation study on a simultaneously recorded fNIRS-fMRI dataset. *NeuroImage, 175*, 413–424. https://doi.org/10.1016/j.neuroimage.2018.04.022

Bulgarelli, C., Blasi, A., De Klerk, C. C. J. M., Richards, J. E., Hamilton, A., & Southgate, V. (2019). Fronto-temporoparietal connectivity and self-awareness in 18-month-olds: A resting state fNIRS study. *Developmental Cognitive Neuroscience, 38*, Article 100676. https://doi.org/10.1016/j.dcn.2019.100676

Buxton, R. B. (2009). *Introduction to Functional Magnetic Resonance Imaging: Principles and Techniques* ((2nd ed.).). Cambridge University Press, 10.1017/CBO9780511605505.

Calderon-Arnulphi, M., Alaraj, A., & Slavin, K. V. (2009). Near infrared technology in neuroscience: Past, present and future. *Neurological Research, 31*(6), 605–614. https://doi.org/10.1179/174313209X383286

Chanda, M. L., & Levitin, D. J. (2013). The neurochemistry of music. *Trends in Cognitive Sciences, 17*(4), 179–193. https://doi.org/10.1016/j.tics.2013.02.007

Chen, W. G., Iversen, J. R., Kao, M. H., Loui, P., Patel, A. D., Zatorre, R. J., & Edwards, E. (2022). Music and Brain Circuitry: Strategies for Strengthening Evidence-Based Research for Music-Based Interventions. *The Journal of Neuroscience, 42*(45), 8498–8507. https://doi.org/10.1523/JNEUROSCI.1135-22.2022

Chen, W.-L., Wagner, J., Heugel, N., Sugar, J., Lee, Y.-W., Conant, L., Malloy, M., Heffernan, J., Quirk, B., Zinos, A., Beardsley, S. A., Prost, R., & Whelan, H. T. (2020). Functional Near-Infrared Spectroscopy and Its Clinical Application in the Field of Neuroscience: Advances and Future Directions. *Frontiers in Neuroscience, 14*, 724. https://doi.org/10.3389/fnins.2020.00724

Cooper, P. K. (2020). It's all in your head: A meta-analysis on the effects of music training on cognitive measures in schoolchildren. *International Journal of Music Education, 38*(3), 321–336. https://doi.org/10.1177/0255761419881495

Cui, X., Bray, S., Bryant, D. M., Glover, G. H., & Reiss, A. L. (2011). A quantitative comparison of NIRS and fMRI across multiple cognitive tasks. *NeuroImage, 54*(4), 2808–2821. https://doi.org/10.1016/j.neuroimage.2010.10.069

Curtin, A., Tong, S., Sun, J., Wang, J., Onaral, B., & Ayaz, H. (2019). A Systematic Review of Integrated Functional Near-Infrared Spectroscopy (fNIRS) and Transcranial Magnetic Stimulation (TMS) Studies. *Frontiers in Neuroscience, 13*, 84. https://doi.org/10.3389/fnins.2019.00084

Curzel, F., Brigadoi, S., & Cutini, S. (2021). fNIRS & e-drum: An ecological approach to monitor hemodynamic and behavioural effects of rhythmic auditory cueing training. *Brain and Cognition, 151*, 105753. https://doi.org/10.1016/J.BANDC.2021.105753

Cutini, S., & Brigadoi, S. (2014). Unleashing the future potential of functional near-infrared spectroscopy in brain sciences. *Journal of Neuroscience Methods*. https://doi.org/10.1016/j.jneumeth.2014.05.024

Czeszumski, A., Eustergerling, S., Lang, A., Menrath, D., Gerstenberger, M., Schuberth, S., Schreiber, F., Rendon, Z. Z., & König, P. (2020). Hyperscanning: A Valid Method to Study Neural Inter-brain Underpinnings of Social Interaction. *Frontiers in Human Neuroscience, 14*. https://www.frontiersin.org/articles/10.3389/fnhum.2020.00039.

Da, C., Jj, L., Metting, Z., Se, R., Jm, S., Jwj, E., & van der Naalt, J. (2021). The feasibility of fNIRS as a diagnostic tool for pediatric TBI: A pilot study. *European Journal of Paediatric Neurology, 30*, 22–24. https://doi.org/10.1016/j.ejpn.2020.12.008

Da Silva Ferreira Barreto, C., Zimeo Morais, G. A., Vanzella, P., & Sato, J. R. (2020). Combining the intersubject correlation analysis and the multivariate distance matrix regression to evaluate associations between fNIRS signals and behavioral data from ecological experiments. *Experimental Brain Research 2020 238:10, 238*(10), 2399–2408. doi: 10.1007/S00221-020-05895-8.

Daikoku, T., Ogura, H., & Watanabe, M. (2012). The variation of hemodynamics relative to listening to consonance or dissonance during chord progression. *Neurological Research, 34*(6), 557–563. https://doi.org/10.1179/1743132812Y.0000000047

Dalla Bella, S., Benoit, C.-E., Farrugia, N., Schwartze, M., & Kotz, S. A. (2015). Effects of musically cued gait training in Parkinson's disease: Beyond a motor benefit. *Annals of the New York Academy of Sciences, 1337*, 77–85. https://doi.org/10.1111/nyas.12651

Delpy, D. T., & Cope, M. (1997). Quantification in tissue near-infrared spectroscopy. *Philosophical Transactions of the Royal Society B: Biological Sciences, 352*(1354), 649–659. https://doi.org/10.1098/rstb.1997.0046

Delpy, D. T., Cope, M., Zee, P. V. D., Arridge, S., Wray, S., & Wyatt, J. (1988). Estimation of optical pathlength through tissue from direct time of flight measurement. *Physics in Medicine and Biology, 33*(12), 1433–1442. https://doi.org/10.1088/0031-9155/33/12/008

Di Lorenzo, R., Pirazzoli, L., Blasi, A., Bulgarelli, C., Hakuno, Y., Minagawa, Y., & Brigadoi, S. (2019). Recommendations for motion correction of infant fNIRS data applicable to multiple data sets and acquisition systems. *NeuroImage, 200*, 511–527. https://doi.org/10.1016/j.neuroimage.2019.06.056

Di Rosa, E., Brigadoi, S., Cutini, S., Tarantino, V., Dell'Acqua, R., Mapelli, D., Braver, T. S., & Vallesi, A. (2019). Reward motivation and neurostimulation interact to improve working memory performance in healthy older adults: A simultaneous tDCS-fNIRS study. *NeuroImage, 202*, Article 116062. https://doi.org/10.1016/j.neuroimage.2019.116062

Doherty, E. J., Spencer, C. A., Burnison, J., Čeko, M., Chin, J., Eloy, L., Haring, K., Kim, P., Pittman, D., Powers, S., Pugh, S. L., Roumis, D., Stephens, J. A., Yeh, T., & Hirshfield, L. (2023). Interdisciplinary views of fNIRS: Current advancements, equity challenges, and an agenda for future needs of a diverse fNIRS research community. *Frontiers in Integrative Neuroscience, 17*, 1059679. https://doi.org/10.3389/fnint.2023.1059679

Duan, L., Zhang, Y.-J., & Zhu, C.-Z. (2012). Quantitative comparison of resting-state functional connectivity derived from fNIRS and fMRI: A simultaneous recording study. *NeuroImage, 60*(4), 2008–2018. https://doi.org/10.1016/j.neuroimage.2012.02.014

Dumas, G. (2011). Towards a two-body neuroscience. *Communicative & Integrative Biology, 4*(3), 349–352. https://doi.org/10.4161/cib.4.3.15110

Eastmond, C., Subedi, A., De, S., & Intes, X. (2022). Deep learning in fNIRS: A review. *Neurophotonics, 9*(04). https://doi.org/10.1117/1.NPh.9.4.041411

Eggebrecht, A. T., Ferradal, S. L., Robichaux-Viehoever, A., Hassanpour, M. S., Dehghani, H., Snyder, A. Z., Hershey, T., & Culver, J. P. (2014). Mapping distributed brain function and networks with diffuse optical tomography. *Nature Photonics, 8*(6), 448–454. https://doi.org/10.1038/nphoton.2014.107

Eggebrecht, A. T., White, B. R., Ferradal, S. L., Chen, C., Zhan, Y., Snyder, A. Z., Dehghani, H., & Culver, J. P. (2012). A quantitative spatial comparison of high-density diffuse optical tomography and fMRI cortical mapping. *NeuroImage, 61*(4), 1120–1128. https://doi.org/10.1016/j.neuroimage.2012.01.124

Eggermont, J. J., & Moore, J. K. (2012). Morphological and Functional Development of the Auditory Nervous System. In L. Werner, R. R. Fay, & A. N. Popper (Eds.), *Human Auditory Development* (Vol. 42, pp. 61–105). New York: Springer. https://doi.org/10.1007/978-1-4614-1421-6_3.

Emberson, L. L., Zinszer, B. D., Raizada, R. D. S., & Aslin, R. N. (2017). Decoding the infant mind: Multivariate pattern analysis (MVPA) using fNIRS. *PLOS ONE, 12*(4), e0172500.

Falk, T. H., Guirgis, M., Power, S., & Chau, T. T. (2011). Taking NIRS-BCIs Outside the Lab: Towards Achieving Robustness Against Environment Noise. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 19*(2), 136–146. https://doi.org/10.1109/TNSRE.2010.2078516

Fantini, S., & Sassaroli, A. (2020). Frequency-Domain Techniques for Cerebral and Functional Near-Infrared Spectroscopy. *Frontiers in Neuroscience, 14*. https://www.frontiersin.org/articles/10.3389/fnins.2020.00300.

Fava, E., Hull, R., Baumbauer, K., & Bortfeld, H. (2014). Hemodynamic responses to speech and music in preverbal infants. *Child Neuropsychology, 20*(4), 430–448. https://doi.org/10.1080/09297049.2013.803524

Fekete, T., Rubin, D., Carlson, J. M., & Mujica-Parodi, L. R. (2011). The NIRS Analysis Package: Noise Reduction and Statistical Inference. *PLoS ONE, 6*(9), e24322.

Feng, K., Shen, C.-Y., Ma, X.-Y., Chen, G.-F., Zhang, M.-L., Xu, B., Liu, X.-M., Sun, J.-J., Zhang, X.-Q., Liu, P.-Z., & Ju, Y. (2019). Effects of music therapy on major depressive disorder: A study of prefrontal hemodynamic functions using fNIRS. *Psychiatry Research, 275*, 86–93. https://doi.org/10.1016/j.psychres.2019.03.015

Fernandez Rojas, R., Huang, X., & Ou, K.-L. (2019). A Machine Learning Approach for the Identification of a Biomarker of Human Pain using fNIRS. *Scientific Reports, 9*(1), 5645. https://doi.org/10.1038/s41598-019-42098-w

Ferradal, S. L., Eggebrecht, A. T., Hassanpour, M., Snyder, A. Z., & Culver, J. P. (2014). Atlas-based head modeling and spatial normalization for high-density diffuse optical tomography: In vivo validation against fMRI. *NeuroImage, 85*, 117–126. https://doi.org/10.1016/j.neuroimage.2013.03.069

Ferrari, M., & Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *NeuroImage, 63*(2), 921–935. https://doi.org/10.1016/j.neuroimage.2012.03.049

Ferreri, L., Aucouturier, J., Muthalib, M., Bigand, E., & Bugaiska, A. (2013). Music improves verbal memory encoding while decreasing prefrontal cortex activity: An fNIRS study. *Frontiers in Human Neuroscience*, (NOV), 779. https://doi.org/10.3389/FNHUM.2013.00779

Ferreri, L., Bigand, E., Bard, P., & Bugaiska, A. (2015). The Influence of Music on Prefrontal Cortex during Episodic Encoding and Retrieval of Verbal Information: A Multichannel fNIRS Study. *Behavioural Neurology, 2015*. https://doi.org/10.1155/2015/707625

Ferreri, L., Bigand, E., Perrey, S., & Bugaïska, A. (2014a). The promise of Near-Infrared Spectroscopy (NIRS) for psychological research: A brief review. *L'Année psychologique, 114*(3), 537–569. https://doi.org/10.3917/anpsy.143.0537

Ferreri, L., Mas-Herrero, E., Zatorre, R. J., Ripollés, P., Gomez-Andres, A., Alicart, H., Olivé, G., Marco-Pallarés, J., Antonijoan, R. M., Valle, M., Riba, J., & Rodriguez-Fornells, A. (2019). Dopamine modulates the reward experiences elicited by music. *Proceedings of the National Academy of Sciences of the United States of America, 116*(9), 3793–3798. doi: 10.1073/pnas.1811878116.

Ferreri, L., Bigand, E., Perrey, S., Muthalib, M., Bard, P., & Bugaiska, A. (2014b). Less Effort, Better Results: How Does Music Act on Prefrontal Cortex in Older Adults during Verbal Encoding? An fNIRS Study. *Frontiers in Human Neuroscience, 8*. https://doi.org/10.3389/fnhum.2014.00301

Ferreri, L., & Rodriguez-Fornells, A. (2022). Memory modulations through musical pleasure. *Annals of the New York Academy of Sciences, 1516*(1), 5–10. https://doi.org/10.1111/nyas.14867

Fishburn, F. A., Ludlum, R. S., Vaidya, C. J., & Medvedev, A. V. (2019). Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. *NeuroImage, 184*, 171–179. https://doi.org/10.1016/j.neuroimage.2018.09.025

Fishburn, F. A., Norr, M. E., Medvedev, A. V., & Vaidya, C. J. (2014). Sensitivity of fNIRS to cognitive state and load. *Frontiers in Human Neuroscience, 8*. https://doi.org/10.3389/fnhum.2014.00076

Fiveash, A., Ferreri, L., Bouwer, F. L., Kösem, A., Moghimi, S., Ravignani, A., Keller, P. E., & Tillmann, B. (2023). Can rhythm-mediated reward boost learning, memory, and social connection? Perspectives for future research. *Neuroscience & Biobehavioral Reviews, 149*, Article 105153. https://doi.org/10.1016/j.neubiorev.2023.105153

Fu, X., & Richards, J. E. (2021). devfOLD: A toolbox for designing age-specific fNIRS channel placement. *Neurophotonics, 8*(4), Article 045003. https://doi.org/10.1117/1.NPh.8.4.045003

Fukui, H., & Toyoshima, K. (2014). Chill-inducing music enhances altruism in humans. *Frontiers in Psychology, 5*, 1215. https://doi.org/10.3389/fpsyg.2014.01215

Fukuie, T., Suwabe, K., Kawase, S., Shimizu, T., Ochi, G., Kuwamizu, R., Sakairi, Y., & Soya, H. (2022). Groove rhythm stimulates prefrontal cortex function in groove enjoyers. *Scientific Reports, 12(1), Article 1*. https://doi.org/10.1038/s41598-022-11324-3

Gagnon, L., Perdue, K., Greve, D. N., Goldenholz, D., Kaskhedikar, G., & Boas, D. A. (2011). Improved recovery of the hemodynamic response in diffuse optical imaging using short optode separations and state-space modeling. *NeuroImage, 56*(3), 1362–1371. https://doi.org/10.1016/j.neuroimage.2011.03.001

Gemignani, J., de la Cruz-Pavía, I., Martinez, A., Nallet, C., Pasquini, A., Lucarini, G., Cavicchiolo, F., & Gervain, J. (2023). Reproducibility of infant fNIRS studies: A meta-analytic approach. *Neurophotonics, 10*(2), Article 023518. https://doi.org/10.1117/1.NPh.10.2.023518

Gervain, J., Minagawa, Y., Emberson, L., & Lloyd-Fox, S. (2023). Using functional near-infrared spectroscopy to study the early developing brain: Future directions and new challenges. *Neurophotonics, 10*(2), Article 023519. https://doi.org/10.1117/1.NPh.10.2.023519

Ghafoor, U., Yang, D., & Hong, K.-S. (2022). Neuromodulatory Effects of HD-tACS/tDCS on the Prefrontal Cortex: A Resting-State fNIRS-EEG Study. *IEEE Journal of Biomedical and Health Informatics, 26*(5), 2192–2203. https://doi.org/10.1109/JBHI.2021.3127080

Gibson, C., Folley, B. S., & Park, S. (2009). Enhanced divergent thinking and creativity in musicians: A behavioral and near-infrared spectroscopy study. *Brain and Cognition, 69*(1), 162–169. https://doi.org/10.1016/j.bandc.2008.07.009

Gordon, R. L., Magne, C. L., & Large, E. W. (2011). EEG Correlates of Song Prosody: A New Look at the Relationship between Linguistic and Musical Rhythm. *Frontiers in Psychology, 2*. https://doi.org/10.3389/fpsyg.2011.00352

Gramfort, A. (2013). MEG and EEG data analysis with MNE-Python. *Frontiers in Neuroscience, 7*. https://doi.org/10.3389/fnins.2013.00267

Gramigna, V., Pellegrino, G., Cerasa, A., Cutini, S., Vasta, R., Olivadese, G., Martino, I., & Quattrone, A. (2017). Near-Infrared Spectroscopy in Gait Disorders: Is It Time to Begin? *In Neurorehabilitation and Neural Repair*. https://doi.org/10.1177/1545968317693304

Gvirts, H. Z., & Perlmutter, R. (2020). What Guides Us to Neurally and Behaviorally Align With Anyone Specific? A Neurobiological Model Based on fNIRS Hyperscanning Studies. *The Neuroscientist, 26*(2), 108–116. https://doi.org/10.1177/1073858419861912

Gvirts Problovski, H., Sharma, M., Gutman, I., Dahan, A., Pan, Y., Stotler, J., & Wilcox, T. (2023). New Framework for Understanding Cross-Brain Coherence in Functional Near-Infrared Spectroscopy (fNIRS) Hyperscanning Studies. *Journal of Visualized Experiments*. https://doi.org/10.3791/65347

Hall, D. A., Haggard, M. P., Akeroyd, M. A., Palmer, A. R., Summerfield, A. Q., Elliott, M. R., Gurney, E. M., & Bowtell, R. W. (1999). "Sparse" temporal sampling in auditory fMRI. *Human Brain Mapping, 7*(3), 213–223. https://doi.org/10.1002/(SICI)1097-0193(1999)7:3<213::AID-HBM5>3.0.CO;2-N

Halpern, A. R. (2001). *Cerebral substrates of musical imagery., 930*, 179–192. https://doi.org/10.1111/j.1749-6632.2001.tb05733.x

Hashimoto, K., Tategami, S., Okamoto, T., Seta, H., Abo, M., & Ohashi, M. (2006). Examination by Near-Infrared Spectroscopy for Evaluation of Piano Performance as a Frontal Lobe Activation Task. *European Neurology, 55*(1), 16–21. https://doi.org/10.1159/000091138

Heard, M., & Lee, Y. S. (2020). Shared neural resources of rhythm and syntax: An ALE meta-analysis. *Neuropsychologia, 137*, Article 107284. https://doi.org/10.1016/j.neuropsychologia.2019.107284

Herholz, S. C., Lappe, C., Knief, A., & Pantev, C. (2008). Neural basis of music imagery and the effect of musical expertise. *European Journal of Neuroscience, 28*(11), 2352–2360. https://doi.org/10.1111/j.1460-9568.2008.06515.x

Herholz, S. C., & Zatorre, R. J. (2012). Musical Training as a Framework for Brain Plasticity: Behavior, Function, and Structure. *Neuron, 76*(3), 486–502. https://doi.org/10.1016/j.neuron.2012.10.011

Herold, F., Wiegel, P., Scholkmann, F., & Müller, N. G. (2018). Applications of Functional Near-Infrared Spectroscopy (fNIRS) Neuroimaging in Exercise-Cognition Science: A Systematic, Methodology-Focused Review. *Journal of Clinical Medicine, 7(12), Article 12*. https://doi.org/10.3390/jcm7120466

Hocke, L., Oni, I., Duszynski, C., Corrigan, A., Frederick, B., & Dunn, J. (2018). Automated Processing of fNIRS Data—A Visual Guide to the Pitfalls and Consequences. *Algorithms, 11*(5), 67. https://doi.org/10.3390/a11050067

Homae, F., Watanabe, H., Nakano, T., & Taga, G. (2012). Functional development in the infant brain for auditory pitch processing. *Human Brain Mapping, 33*(3), 596–608. https://doi.org/10.1002/HBM.21236

Hong, K. S., & Santosa, H. (2016). Decoding four different sound-categories in the auditory cortex using functional near-infrared spectroscopy. *Hearing Research, 333*, 157–166. https://doi.org/10.1016/J.HEARES.2016.01.009

Hou, X., Zhang, Z., Zhao, C., Duan, L., Gong, Y., Li, Z., & Zhu, C. (2021). NIRS-KIT: A MATLAB toolbox for both resting-state and task fNIRS data analysis. *Neurophotonics, 8*(01). https://doi.org/10.1117/1.NPh.8.1.010802

Hou, Y., Song, B., Hu, Y., Pan, Y., & Hu, Y. (2020). The averaged inter-brain coherence between the audience and a violinist predicts the popularity of violin performance. *NeuroImage, 211*, 116655. https://doi.org/10.1016/J.NEUROIMAGE.2020.116655

Huppert, T. J. (2016). Commentary on the statistical properties of noise and its implication on general linear models in functional near-infrared spectroscopy. *Neurophotonics, 3*(1), Article 010401. https://doi.org/10.1117/1.NPh.3.1.010401

Huppert, T. J., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2009). HomER: A review of time-series analysis methods for near-infrared spectroscopy of the brain. *Applied Optics, 48*(10), D280. https://doi.org/10.1364/AO.48.00D280

Huppert, T. J., Hoge, R. D., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2006). A temporal comparison of BOLD, ASL, and NIRS hemodynamic responses to motor stimuli in adult humans. *NeuroImage, 29*(2), 368–382. https://doi.org/10.1016/j.neuroimage.2005.08.065

Huron, D. (2006). Sweet Anticipation: Music and the Psychology of Expectation. *The MIT Press*. https://doi.org/10.7551/mitpress/6575.001.0001

Irani, F., Platek, S. M., Bunce, S., Ruocco, A. C., & Chute, D. (2007). Functional Near Infrared Spectroscopy (fNIRS): An Emerging Neuroimaging Technology with Important Applications for the Study of Brain Disorders. *The Clinical Neuropsychologist, 21*(1), 9–37. https://doi.org/10.1080/13854040600910018

Izen, S. C., Cassano-Coleman, R. Y., & Piazza, E. A. (2023). Music as a window into real-world communication. *Frontiers in Psychology, 14*, 1012839. https://doi.org/10.3389/fpsyg.2023.1012839

Izzetoglu, M., Bunce, S. C., Izzetoglu, K., Onaral, B., Pourrezaei, & Kambiz. (2007). Functional brain imaging using near-infrared technology. *IEEE Engineering in Medicine and Biology Magazine, 26*(4), 38–46. https://doi.org/10.1109/MEMB.2007.384094

Janata, P., Tomic, S. T., & Haberman, J. M. (2012). Sensorimotor coupling in music and the psychology of the groove. *Journal of Experimental Psychology: General, 141*(1), 54–75. https://doi.org/10.1037/a0024208

Jeong, E., & Ryu, H. (2016a). Melodic Contour Identification Reflects the Cognitive Threshold of Aging. *Frontiers in Aging Neuroscience, 8*. https://doi.org/10.3389/fnagi.2016.00134

Jeong, E., & Ryu, H. (2016b). Nonverbal auditory working memory: Can music indicate the capacity? *Brain and Cognition, 105*, 9–21. https://doi.org/10.1016/j.bandc.2016.03.003

Jeong, E., Ryu, H., Jo, G., & Kim, J. (2018a). Cognitive Load Changes during Music Listening and its Implication in Earcon Design in Public Environments: An fNIRS Study. *International Journal of Environmental Research and Public Health, 15*(10), Article 10. https://doi.org/10.3390/ijerph15102075

Jeong, E., Ryu, H., Shin, J.-H., Kwon, G. H., Jo, G., & Lee, J.-Y. (2018b). High Oxygen Exchange to Music Indicates Auditory Distractibility in Acquired Brain Injury: An fNIRS Study with a Vector-Based Phase Analysis. *Scientific Reports, 8*(1), 16737. https://doi.org/10.1038/s41598-018-35172-2

Jöbsis, F. F. (1977). Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. *Science (New York, N.Y.), 198*(4323), 1264–1267.

Juslin, P. N., & Västfjäll, D. (2008). Emotional responses to music: The need to consider underlying mechanisms. *Behavioral and Brain Sciences, 31*(5), 559–575. https://doi.org/10.1017/S0140525X08005293

Kirlilna, E., Yu, N., Jelzow, A., Wabnitz, H., Jacobs, A. M., & Tachtsidis, I. (2013). Identifying and quantifying main components of physiological noise in functional near infrared spectroscopy on the prefrontal cortex. *Frontiers in Human Neuroscience, 7*. https://doi.org/10.3389/fnhum.2013.00864

Klein, F., Debener, S., Witt, K., & Kranczioch, C. (2022a). fMRI-based validation of continuous-wave fNIRS of supplementary motor area activation during motor execution and motor imagery. *Scientific Reports, 12*(1), 3570. https://doi.org/10.1038/s41598-022-06519-7

Klein, F., Lührs, M., Benitez-Andonegui, A., Roehn, P., & Kranczioch, C. (2022b). Performance comparison of systemic activity correction in functional near-infrared spectroscopy for methods with and without short distance channels. *Neurophotonics, 10*(01). https://doi.org/10.1117/1.NPh.10.1.013503

Koelsch, S. (2011). Toward a Neural Basis of Music Perception – A Review and Updated Model. *Frontiers in Psychology, 2*. https://www.frontiersin.org/articles/10.3389/fpsyg.2011.00110.

Koelsch, S. (2013). From Social Contact to Social Cohesion—The 7 Cs. *Music and Medicine, 5*(4), 204–209. https://doi.org/10.1177/1943862113508588

Koelsch, S. (2014). Brain correlates of music-evoked emotions. *Nature Reviews Neuroscience, 15*(3), 170–180. https://doi.org/10.1038/nrn3666

Kotilahti, K., Nissilä, I., Näsi, T., Lipiäinen, L., Noponen, T., Meriläinen, P., Huotilainen, M., & Fellman, V. (2010). Hemodynamic responses to speech and music in newborn infants. *Human Brain Mapping, 31*(4), 595–603. https://doi.org/10.1002/hbm.20890

Kovelman, I., Mascho, K., Millott, L., Mastic, A., Moiseff, B., Shalinsky, H., & M.. (2012). At the rhythm of language: Brain bases of language-related frequency perception in children. *NeuroImage, 60*(1), 673–682. https://doi.org/10.1016/j.neuroimage.2011.12.066

Kulinski, J., Ofori, E. K., Visotcky, A., Smith, A., Sparapani, R., & Fleg, J. L. (2022). Effects of music on the cardiovascular system. *Trends in Cardiovascular Medicine, 32* (6), 390–398. https://doi.org/10.1016/j.tcm.2021.06.004

Kwasa, J., Peterson, H. M., Karrobi, K., Jones, L., Parker, T., Nickerson, N., & Wood, S. (2023). Demographic reporting and phenotypic exclusion in fNIRS. *Frontiers in Neuroscience, 17*. https://www.frontiersin.org/articles/10.3389/fnins.2023.1086208.

Lee, G., Ro, D., Shin, S., & Kim, Y.-H. (2023). HyperOptoNet: A MATLAB-based toolbox for inter-brain neuronal synchrony analysis using fNIRS hyperscanning. *Neurophotonics, 10*(2), Article 025015. https://doi.org/10.1117/1.NPh.10.2.025015

Li, Q., Feng, J., Guo, J., Wang, Z., Li, P., Liu, H., & Fan, Z. (2020). Effects of the multisensory rehabilitation product for home-based hand training after stroke on cortical activation by using NIRS methods. *Neuroscience Letters, 717*, Article 134682. https://doi.org/10.1016/j.neulet.2019.134682

Li, R., Hosseini, H., Saggar, M., Balters, S. C., & Reiss, A. L. (2023). Current opinions on the present and future use of functional near-infrared spectroscopy in psychiatry. *Neurophotonics, 10*(1), Article 013505. https://doi.org/10.1117/1.NPh.10.1.013505

Li, R., Yang, D., Fang, F., Hong, K.-S., Reiss, A. L., & Zhang, Y. (2022). Concurrent fNIRS and EEG for Brain Function Investigation: A Systematic. *Methodology-Focused Review. Sensors, 22*(15), 5865. https://doi.org/10.3390/s22155865

Liikkanen, L. A., & Jakubowski, K. (2020). Involuntary musical imagery as a component of ordinary music cognition: A review of empirical evidence. *Psychonomic Bulletin and Review, 27*(6), 1195–1217. https://doi.org/10.3758/s13423-020-01750-7

Liu, T., Duan, L., Dai, R., Pelowski, M., & Zhu, C. (2021). Team-work, Team-brain: Exploring synchrony and team interdependence in a nine-person drumming task via multiparticipant hyperscanning and inter-brain network topology with fNIRS. *NeuroImage, 237*, 118147. https://doi.org/10.1016/J.NEUROIMAGE.2021.118147

Lloyd-Fox, S., Begus, K., Halliday, D., Pirazzoli, L., Blasi, A., Papademetriou, M., Darboe, M. K., Prentice, A. M., Johnson, M. H., Moore, S. E., & Elwell, C. E. (2017). Cortical specialisation to social stimuli from the first days to the second year of life: A rural Gambian cohort. *Developmental Cognitive Neuroscience, 25*, 92–104. https://doi.org/10.1016/j.dcn.2016.11.005

Lo, Y. L., Zhang, H. H., Wang, C. C., Chin, Z. Y., Fook-Chong, S., Gabriel, C., & Guan, C. T. (2009). Correlation of Near-Infrared Spectroscopy and Transcranial Magnetic Stimulation of the Motor Cortex in Overt Reading and Musical Tasks. *Motor Control, 13*(1), 84–99. https://doi.org/10.1123/MCJ.13.1.84

Lordier, L., Meskaldji, D.-E., Grouiller, F., Pittet, M. P., Vollenweider, A., Vasung, L., Borradori-Tolsa, C., Lazeyras, F., Grandjean, D., Van De Ville, D., & Hüppi, P. S. (2019). Music in premature infants enhances high-level cognitive brain networks. *Proceedings of the National Academy of Sciences, 116*(24), 12103–12108. https://doi.org/10.1073/pnas.1817536116

Lu, C.-M., Zhang, Y.-J., Biswal, B. B., Zang, Y.-F., Peng, D.-L., & Zhu, C.-Z. (2010). Use of fNIRS to assess resting state functional connectivity. *Journal of Neuroscience Methods, 186*(2), 242–249. https://doi.org/10.1016/j.jneumeth.2009.11.010

Luke, R., Larson, E., Shader, M. J., Innes-Brown, H., Van Yper, L., Lee, A. K. C., Sowman, P. F., & McAlpine, D. (2021). Analysis methods for measuring passive auditory fNIRS responses generated by a block-design paradigm. *Neurophotonics, 8* (02). https://doi.org/10.1117/1.NPh.8.2.025008

Mas-Herrero, E., Dagher, A., & Zatorre, R. J. (2018). Modulating musical reward sensitivity up and down with transcranial magnetic stimulation. *Nature Human Behaviour, 2*(1), Article 1. https://doi.org/10.1038/s41562-017-0241-z

Mas-Herrero, E., Maini, L., Sescousse, G., & Zatorre, R. J. (2021). Common and distinct neural correlates of music and food-induced pleasure: A coordinate-based meta-analysis of neuroimaging studies. *Neuroscience & Biobehavioral Reviews, 123*, 61–71. https://doi.org/10.1016/j.neubiorev.2020.12.008

Mas-Herrero, E., Singer, N., Ferreri, L., McPhee, M., Zatorre, R. J., & Ripollés, P. (2023). Music engagement is negatively correlated with depressive symptoms during the COVID-19 pandemic via reward-related mechanisms. *Annals of the New York Academy of Sciences, 1519*(1), 186–198. https://doi.org/10.1111/nyas.14931

Matthews, T. E., Witek, M. A. G., Lund, T., Vuust, P., & Penhune, V. B. (2020). The sensation of groove engages motor and reward networks. *NeuroImage, 214*, Article 116768. https://doi.org/10.1016/j.neuroimage.2020.116768

Mazzonetto, I., Castellaro, M., Cooper, R. J., & Brigadoi, S. (2022). Smartphone-based photogrammetry provides improved localization and registration of scalp-mounted neuroimaging sensors. *Scientific Reports, 12*(1), Article 1. https://doi.org/10.1038/s41598-022-14458-6

Meder, U., Tarjanyi, E., Kovacs, K., Szakmar, E., Cseko, A. J., Hazay, T., Belteki, G., Szabo, M., & Jermendy, A. (2021). Cerebral oxygenation in preterm infants during maternal singing combined with skin-to-skin care. *Pediatric Research, 90*(4), Article 4. https://doi.org/10.1038/s41390-020-01235-2

Minematsu, Y., Ueji, K., & Yamamoto, T. (2018). Activity of frontal pole cortex reflecting hedonic tone of food and drink: fNIRS study in humans. *Scientific Reports, 8*(1), Article 1. https://doi.org/10.1038/s41598-018-34690-3

Moghimi, S., Kushki, A., Guerguerian, A. M., & Chau, T. (2012a). Characterizing emotional response to music in the prefrontal cortex using near infrared spectroscopy. *Neuroscience Letters, 525*(1), 7–11. https://doi.org/10.1016/j.neulet.2012.07.009

Moghimi, S., Kushki, A., Power, S., Guerguerian, A. M., & Chau, T. (2012b). Automatic detection of a prefrontal cortical response to emotionally rated music using multi-channel near-infrared spectroscopy. *Journal of Neural Engineering, 9*(2), Article 026022. https://doi.org/10.1088/1741-2560/9/2/026022

Moghimi, S., Schudlo, L., Chau, T., & Guerguerian, A.-M. (2015). Variability in Prefrontal Hemodynamic Response during Exposure to Repeated Self-Selected Music Excerpts, a Near-Infrared Spectroscopy Study. *PLOS ONE, 10*(4), e0122148.

Montague, P. R., Berns, G. S., Cohen, J. D., McClure, S. M., Pagnoni, G., Dhamala, M., Wiest, M. C., Karpov, I., King, R. D., Apple, N., & Fisher, R. E. (2002). Hyperscanning: Simultaneous fMRI during Linked Social Interactions. *NeuroImage, 16*(4), 1159–1164. https://doi.org/10.1006/nimg.2002.1150

Montero-Hernandez, S., & Pollonini, L. (2023). *QT-NIRS (Quality Testing of Near Infrared Scans)* [MATLAB]. https://github.com/lpollonini/qt-nirs (Original work published 2020).

Mowinckel, A. M., & Vidal-Piñeiro, D. (2020). Visualization of Brain Statistics With R Packages *ggseg* and *ggseg3d*. *Advances in Methods and Practices in Psychological Science, 3*(4), 466–483. https://doi.org/10.1177/2515245920928009

Muccigrosso, D., Culver, J. P., & Eggebrecht, A. T. (2018). NeuroDOT: A New Neuroimaging Toolbox for DOT. *Biophotonics Congress: Biomedical Optics Congress 2018 (Microscopy/Translational/Brain/OTS)*, OW4C.7. doi: 10.1364/OTS.2018.OW4C.7.

Naseer, N., & Hong, K. S. (2015). fNIRS-based brain-computer interfaces: A review. *Frontiers in Human Neuroscience, 9*(JAN), 3. https://doi.org/10.3389/fnhum.2015.00003

Nguyen, T., Flaten, E., Trainor, L. J., & Novembre, G. (2023). Early social communication through music: State of the art and future perspectives. *Developmental Cognitive Neuroscience, 63*, Article 101279. https://doi.org/10.1016/j.dcn.2023.101279

Nguyen, T., Hoehl, S., & Vrtička, P. (2021). A Guide to Parent-Child fNIRS Hyperscanning Data Processing and Analysis. *Sensors*, *21*(12), Article 12. doi: 10.3390/s21124075.

Noah, J. A., Ono, Y., Nomoto, Y., Shimada, S., Tachibana, A., Zhang, X., Bronner, S., & Hirsch, J. (2015). fMRI Validation of fNIRS Measurements During a Naturalistic Task. *Journal of Visualized Experiments*, *100*, 52116. https://doi.org/10.3791/52116

Novi, S. L., Rodrigues, R. B. M. L., & Mesquita, R. C. (2016). Resting state connectivity patterns with near-infrared spectroscopy data of the whole head. *Biomedical Optics Express, 7*(7), 2524. https://doi.org/10.1364/BOE.7.002524

Nozaradan, S. (2014). Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1658), 20130393. https://doi.org/10.1098/rstb.2013.0393

Nummenmaa, L., Putkinen, V., & Sams, M. (2021). Social pleasures of music. *Current Opinion in Behavioral Sciences, 39*, 196–202. https://doi.org/10.1016/j.cobeha.2021.03.026

Olszewska, A. M., Droździel, D., Gaca, M., Kulesza, A., Obrębski, W., Kowalewski, J., Widlarz, A., Marchewka, A., & Herman, A. M. (2023). Unlocking the musical brain: A proof-of-concept study on playing the piano in MRI scanner with naturalistic stimuli. *Heliyon, 9*(7), e17877.

Olszewska, A. M., Gaca, M., Herman, A. M., Jednoróg, K., & Marchewka, A. (2021). How Musical Training Shapes the Adult Brain: Predispositions and Neuroplasticity. *Frontiers in Neuroscience, 15*, 204. https://doi.org/10.3389/fnins.2021.630829

Ono, Y., Nomoto, Y., Tanaka, S., Sato, K., Shimada, S., Tachibana, A., Bronner, S., & Noah, J. A. (2014). Frontotemporal oxyhemoglobin dynamics predict performance accuracy of dance simulation gameplay: Temporal characteristics of top-down and bottom-up cortical activities. *NeuroImage, 85*, 461–470. https://doi.org/10.1016/J.NEUROIMAGE.2013.05.071

Orihuela-Espina, F., Leff, D. R., James, D. R. C., Darzi, A. W., & Yang, G. Z. (2010). Quality control and assurance in functional near infrared spectroscopy (fNIRS) experimentation. *Physics in Medicine and Biology, 55*(13), 3701–3724. https://doi.org/10.1088/0031-9155/55/13/009

Osaka, N., Minamoto, T., Yaoi, K., Azuma, M., Shimada, Y. M., & Osaka, M. (2015). How Two Brains Make One Synchronized Mind in the Inferior Frontal Cortex: fNIRS-Based Hyperscanning During Cooperative Singing. *Frontiers in Psychology*, (NOV), 1811. https://doi.org/10.3389/FPSYG.2015.01811

Ou, W., Nissilä, I., Radhakrishnan, H., Boas, D. A., Hämäläinen, M. S., & Franceschini, M. A. (2009). Study of neurovascular coupling in humans via simultaneous magnetoencephalography and diffuse optical imaging acquisition. *NeuroImage, 46*(3), 624–632.

Pan, Y., Novembre, G., Song, B., Li, X., & Hu, Y. (2018). Interpersonal synchronization of inferior frontal cortices tracks social interactive learning of a song. *NeuroImage, 183*, 280–290. https://doi.org/10.1016/J.NEUROIMAGE.2018.08.005

Parsons, L. M., Sergent, J., Hodges, D. A., & Fox, P. T. (2005). The brain basis of piano performance. *Neuropsychologia, 43*(2), 199–215. https://doi.org/10.1016/j.neuropsychologia.2004.11.007

Patil, A. V., Safaie, J., Moghaddam, H. A., Wallois, F., & Grebe, R. (2011). Experimental investigation of NIRS spatial sensitivity. *Biomedical Optics Express, 2*(6), 1478. https://doi.org/10.1364/BOE.2.001478

Perani, D., Saccuman, M. C., Scifo, P., Spada, D., Andreolli, G., Rovelli, R., Baldoli, C., & Koelsch, S. (2010). Functional specializations for music processing in the human newborn brain. *Proceedings of the National Academy of Sciences, 107*(10), 4758–4763. https://doi.org/10.1073/pnas.0909074107

Perdue, K. L., Jensen, S. K. G., Kumar, S., Richards, J. E., Kakon, S. H., Haque, R., Petri, W. A., Jr, Lloyd-Fox, S., Elwell, C., & Nelson, C. A. (2019). Using functional near-infrared spectroscopy to assess social information processing in poor urban Bangladeshi infants and toddlers. *Developmental Science, 22*(5), e12839.

Pereira, A. P. S., Marinho, V., Gupta, D., Magalhães, F., Ayres, C., & Teixeira, S. (2019). Music Therapy and Dance as Gait Rehabilitation in Patients With Parkinson Disease: A Review of Evidence. *Journal of Geriatric Psychiatry and Neurology, 32*(1), 49–56. https://doi.org/10.1177/0891988718819858

Peretz, I., Gosselin, N., Belin, P., Zatorre, R. J., Plailly, J., & Tillmann, B. (2009). Music Lexical Networks: The Cortical Organization of Music Recognition. *Annals of the New York Academy of Sciences, 1169*(1), 256–265. https://doi.org/10.1111/j.1749-6632.2009.04557.x

Perrey, S. (2008). Non-invasive NIR spectroscopy of human brain function during exercise. *Methods, 45*(4), 289–299. https://doi.org/10.1016/j.ymeth.2008.04.005

Pineda, R., Guth, R., Herring, A., Reynolds, L., Oberle, S., & Smith, J. (2017). Enhancing sensory experiences for very preterm infants in the NICU: An integrative review. *Journal of Perinatology, 37*(4), Article 4. https://doi.org/10.1038/jp.2016.179

Pinti, P., Aichelburg, C., Gilbert, S., Hamilton, A., Hirsch, J., Burgess, P., & Tachtsidis, I. (2018). A Review on the Use of Wearable Functional Near-Infrared Spectroscopy in Naturalistic Environments. *Japanese Psychological Research, 60*(4), 347–373. https://doi.org/10.1111/jpr.12206

Pinti, P., Scholkmann, F., Hamilton, A., Burgess, P., & Tachtsidis, I. (2019). Current Status and Issues Regarding Pre-processing of fNIRS Neuroimaging Data: An Investigation of Diverse Signal Filtering Methods Within a General Linear Model Framework. *Frontiers in Human Neuroscience, 12*, 505. https://doi.org/10.3389/fnhum.2018.00505

Pinti, P., Tachtsidis, I., Hamilton, A., Hirsch, J., Aichelburg, C., Gilbert, S., & Burgess, P. W. (2020). The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience. *Annals of the New York Academy of Sciences, 1464*(1), 5–29. https://doi.org/10.1111/nyas.13948

Piper, S. K., Krueger, A., Koch, S. P., Mehnert, J., Habermehl, C., Steinbrink, J., Obrig, H., & Schmitz, C. H. (2014). A wearable multi-channel fNIRS system for brain imaging in freely moving subjects. *NeuroImage, 85*, 64–71. https://doi.org/10.1016/J.NEUROIMAGE.2013.06.062

Platel, H., Baron, J.-C., Desgranges, B., Bernard, F., & Eustache, F. (2003). Semantic and episodic memory of music are subserved by distinct neural networks. *NeuroImage, 20*(1), 244–256. https://doi.org/10.1016/S1053-8119(03)00287-8

Plichta, M. M., Gerdes, A. B. M., Alpers, G. W., Harnisch, W., Brill, S., Wieser, M. J., & Fallgatter, A. J. (2011). Auditory cortex activation is modulated by emotion: A functional near-infrared spectroscopy (fNIRS) study. *NeuroImage, 55*(3), 1200–1207. https://doi.org/10.1016/J.NEUROIMAGE.2011.01.011

Plichta, M. M., Herrmann, M. J., Baehne, C. G., Ehlis, A.-C., Richter, M. M., Pauli, P., & Fallgatter, A. J. (2006). Event-related functional near-infrared spectroscopy (fNIRS): Are the measurements reliable? *NeuroImage, 31*(1), 116–124. https://doi.org/10.1016/j.neuroimage.2005.12.008

Poline, J.-B., & Brett, M. (2012). The general linear model and fMRI: Does love last forever? *NeuroImage, 62*(2), 871–880. https://doi.org/10.1016/j.neuroimage.2012.01.133

Pollonini, L., Bortfeld, H., & Oghalai, J. S. (2016). PHOEBE: A method for real time mapping of optodes-scalp coupling in functional near-infrared spectroscopy. *Biomedical Optics Express, 7*(12), 5104. https://doi.org/10.1364/BOE.7.005104

Power, S. D., Falk, T. H., & Chau, T. (2010). Classification of prefrontal activity due to mental arithmetic and music imagery using hidden Markov models and frequency domain near-infrared spectroscopy. *Journal of Neural Engineering, 7*(2), Article 026002. https://doi.org/10.1088/1741-2560/7/2/026002

Power, S. D., Kushki, A., & Chau, T. (2011). Towards a system-paced near-infrared spectroscopy brain–computer interface: Differentiating prefrontal activity due to mental arithmetic and mental singing from the no-control state. *Journal of Neural Engineering, 8*(6), Article 066004. https://doi.org/10.1088/1741-2560/8/6/066004

Power, S. D., Kushki, A., & Chau, T. (2012). Automatic single-trial discrimination of mental arithmetic, mental singing and the no-control state from prefrontal activity: Toward a three-state NIRS-BCI. *BMC Research Notes, 5*(1), 141. https://doi.org/10.1186/1756-0500-5-141

Putkinen, V., Nazari-Farsani, S., Seppälä, K., Karjalainen, T., Sun, L., Karlsson, H. K., Hudson, M., Heikkilä, T. T., Hirvonen, J., & Nummenmaa, L. (2021). Decoding Music-Evoked Emotions in the Auditory and Motor Cortex. *Cerebral Cortex, 31*(5), 2549–2560. https://doi.org/10.1093/cercor/bhaa373

Qiu, L., Zhong, Y., Xie, Q., He, Z., Wang, X., Chen, Y., Zhan, C. A., & Pan, J. (2022). Multi-Modal Integration of EEG-fNIRS for Characterization of Brain Activity Evoked by Preferred Music. *Frontiers in Neurorobotics, 16*. https://www.frontiersin.org/articles/10.3389/fnbot.2022.823435.

Raglio, A., Attardo, L., Gontero, G., Rollino, S., Groppo, E., & Granieri, E. (2015). Effects of music and music therapy on mood in neurological patients. *World Journal of Psychiatry, 5*(1), 68–78. https://doi.org/10.5498/wjp.v5.i1.68

Rahman, M. A., Siddik, A. B., Ghosh, T. K., Khanam, F., & Ahmad, M. (2020). A Narrative Review on Clinical Applications of fNIRS. *Journal of Digital Imaging, 33*(5), 1167–1184. https://doi.org/10.1007/s10278-020-00387-1

Redcay, E., & Schilbach, L. (2019). Using second-person neuroscience to elucidate the mechanisms of social interaction. *Nature Reviews Neuroscience, 20*(8). https://doi.org/10.1038/s41583-019-0179-4. Article 8.

Ren, H., Zou, L., Wang, L., Lu, C., Yuan, Y., Dai, C., & Chen, W. (2021). Evaluation of the Short-Term Music Therapy on Brain Functions of Preterm Infants Using Functional Near-Infrared Spectroscopy. *Frontiers in Neurology, 12*. https://www.frontiersin.org/articles/10.3389/fneur.2021.649340.

Ripollés, P., Rojo, N., Grau-Sánchez, J., Amengual, J. L., Càmara, E., Marco-Pallarés, J., Juncadella, M., Vaquero, L., Rubio, F., Duarte, E., Garrido, C., Altenmüller, E., Münte, T. F., & Rodríguez-Fornells, A. (2016). Music supported therapy promotes motor plasticity in individuals with chronic stroke. *Brain Imaging and Behavior, 10*(4), 1289–1307. https://doi.org/10.1007/s11682-015-9498-x

Rojiani, R., Zhang, X., Noah, A., & Hirsch, J. (2018). Communication of emotion via drumming: Dual-brain imaging with functional near-infrared spectroscopy. *Social Cognitive and Affective Neuroscience, 13*(10), 1047–1057. https://doi.org/10.1093/SCAN/NSY076

Román-Caballero, R., Vadillo, M. A., Trainor, L. J., & Lupiáñez, J. (2022). Please don't stop the music: A meta-analysis of the cognitive and academic benefits of instrumental musical training in childhood and adolescence. *Educational Research Review, 35*, Article 100436. https://doi.org/10.1016/j.edurev.2022.100436

Rossi, S., Gugler, M. F., Rungger, M., Galvan, O., Zorowka, P. G., & Seebacher, J. (2020). How the Brain Understands Spoken and Sung Sentences. *Brain Sciences 2020, Vol. 10, Page 36*, *10*(1), 36–36. doi: 10.3390/BRAINSCI10010036.

Rostrup, E., Law, I., Pott, F., Ide, K., & Knudsen, G. M. (2002). Cerebral hemodynamics measured with simultaneous PET and near-infrared spectroscopy in humans. *Brain research, 954*(2), 183–193.

Ru, X., He, K., Lyu, B., Li, D., Xu, W., Gu, W., Ma, X., Liu, J., Li, C., Li, T., Zheng, F., Yan, X., Yin, Y., Duan, H., Na, S., Wan, S., Qin, J., Sheng, J., & Gao, J.-H. (2022). Multimodal neuroimaging with optically pumped magnetometers: A simultaneous MEG-EEG-fNIRS acquisition system. *NeuroImage, 259*, Article 119420. https://doi.org/10.1016/j.neuroimage.2022.119420

Saitou, H., Yanagi, H., Hara, S., Tsuchiya, S., & Tomura, S. (2000). Cerebral blood volume and oxygenation among poststroke hemiplegic patients: Effects of 13 rehabilitation tasks measured by near-Infrared spectroscopy. *Archives of Physical Medicine and Rehabilitation, 81*(10), 1348–1356. https://doi.org/10.1053/APMR.2000.9400

Sakatani, K., Chen, S., Lichty, W., Zuo, H., & Wang, Y.p. (1999). Cerebral blood oxygenation changes induced by auditory stimulation in newborn infants measured by near infrared spectroscopy. *Early Human Development, 55*(3), 229–236. https://doi.org/10.1016/S0378-3782(99)00019-5

Saliba, J., Bortfeld, H., Levitin, D. J., & Oghalai, J. S. (2016). Functional near-infrared spectroscopy for neuroimaging in cochlear implant recipients. *Hearing Research, 338*, 64–75. https://doi.org/10.1016/J.HEARES.2016.02.005

Salimpoor, V. N., van den Bosch, I., Kovacevic, N., McIntosh, A. R., Dagher, A., & Zatorre, R. J. (2013). Interactions Between the Nucleus Accumbens and Auditory Cortices Predict Music Reward Value. *Science, 340*(6129), 216–219. https://doi.org/10.1126/science.1231059

Salimpoor, V. N., Zald, D. H., Zatorre, R. J., Dagher, A., & McIntosh, A. R. (2015). Predictions and the brain: How musical sounds become rewarding. *Trends in Cognitive Sciences, 19*(2), 86–91. https://doi.org/10.1016/j.tics.2014.12.001

Samson, S., Dellacherie, D., & Platel, H. (2009). Emotional Power of Music in Patients with Memory Disorders. *Annals of the New York Academy of Sciences, 1169*(1), 245–255. https://doi.org/10.1111/j.1749-6632.2009.04555.x

Santosa, H., Hong, M. J., & Hong, K.-S. (2014). Lateralization of music processing with noises in the auditory cortex: An fNIRS study. *Frontiers in Behavioral Neuroscience*, (DEC), 418. https://doi.org/10.3389/FNBEH.2014.00418

Santosa, H., Zhai, X., Fishburn, F., & Huppert, T. (2018). *The NIRS Brain AnalyzIR Toolbox. Algorithms, 11*(5), 73. https://doi.org/10.3390/a11050073

Sarinasadat, H., Hattori, Y., Miyake, Y., & Nozawa, T. (2019). Music Valence and Genre Influence Group Creativity. In D. Harris (Ed.), *Engineering Psychology and Cognitive Ergonomics* (pp. 410–422). Springer International Publishing. https://doi.org/10.1007/978-3-030-22507-0_32.

Särkämö, T., Tervaniemi, M., & Huotilainen, M. (2013). Music perception and cognition: Development, neural basis, and rehabilitative use of music. *Wiley Interdisciplinary Reviews: Cognitive Science, 4*(4), 441–451. https://doi.org/10.1002/wcs.1237

Savage, P. E., Loui, P., Tarr, B., Schachner, A., Glowacki, L., Mithen, S., & Fitch, W. T. (2021). Music as a coevolved system for social bonding. *Behavioral and Brain Sciences, 44*, e59.

Scarapicchia, V., Brown, C., Mayo, C., & Gawryluk, J. R. (2017). Functional Magnetic Resonance Imaging and Functional Near-Infrared Spectroscopy: Insights from Combined Recording Studies. *Frontiers in Human Neuroscience, 11*, 419. https://doi.org/10.3389/fnhum.2017.00419

Scholkmann, F., Kleiser, S., Metz, A. J., Zimmermann, R., Mata Pavia, J., Wolf, U., & Wolf, M. (2014). A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. *NeuroImage, 85*(Pt 1), 6–27. https://doi.org/10.1016/j.neuroimage.2013.05.004

Shatzer, H. E., & Russo, F. A. (2023). Brightening the Study of Listening Effort with Functional Near-Infrared Spectroscopy: A Scoping Review. *Seminars in Hearing, 44*(02), 188–210. https://doi.org/10.1055/s-0043-1766105

Shimizu, N., Umemura, T., Matsunaga, M., & Hirai, T. (2018). Effects of movement music therapy with a percussion instrument on physical and frontal lobe function in older adults with mild cognitive impairment: A randomized controlled trial. *Aging & Mental Health, 22*(12), 1614–1626. https://doi.org/10.1080/13607863.2017.1379048

Sihvonen, A. J., Särkämö, T., Leo, V., Tervaniemi, M., Altenmüller, E., & Soinila, S. (2017). Music-based interventions in neurological rehabilitation. *The Lancet Neurology, 16*(8), 648–660. https://doi.org/10.1016/S1474-4422(17)30168-0

Singh, A. K., & Dan, I. (2006). Exploring the false discovery rate in multichannel NIRS. *NeuroImage, 33*(2), 542–549. https://doi.org/10.1016/j.neuroimage.2006.06.047

Singh, A. K., Okamoto, M., Dan, H., Jurcak, V., & Dan, I. (2005). Spatial registration of multichannel multi-subject fNIRS data to MNI space without MRI. *NeuroImage, 27*(4), 842–851. https://doi.org/10.1016/j.neuroimage.2005.05.019

Steinbrink, J., Villringer, A., Kempf, F., Haux, D., Boden, S., & Obrig, H. (2006). Illuminating the BOLD signal: Combined fMRI–fNIRS studies. *Magnetic Resonance Imaging, 24*(4), 495–505. https://doi.org/10.1016/j.mri.2005.12.034

Sutoko, S., Sato, H., Maki, A., Kiguchi, M., Hirabayashi, Y., Atsumori, H., Obata, A., Funane, T., & Katura, T. (2016). Tutorial on platform for optical topography analysis tools. *Neurophotonics, 3*(1), Article 010801. https://doi.org/10.1117/1.NPh.3.1.010801

Suwabe, K., Hyodo, K., Fukuie, T., Ochi, G., Inagaki, K., Sakairi, Y., & Soya, H. (2021). Positive Mood while Exercising Influences Beneficial Effects of Exercise with Music on Prefrontal Executive Function: A Functional NIRS Study. *Neuroscience, 454*, 61–71. https://doi.org/10.1016/j.neuroscience.2020.06.007

Tachibana, A., Noah, J. A., Bronner, S., Ono, Y., & Onozuka, M. (2011). Parietal and temporal activity during a multimodal dance video game: An fNIRS study. *Neuroscience Letters, 503*(2), 125–130. https://doi.org/10.1016/j.neulet.2011.08.023

Tachibana, A., Noah, J. A., Ono, Y., Taguchi, D., & Ueda, S. (2019). Prefrontal activation related to spontaneous creativity with rock music improvisation: A functional near-infrared spectroscopy study. *Scientific Reports 2019 9:1, 9*(1), 1–13. doi: 10.1038/s41598-019-52348-6.

Tachtsidis, I., & Scholkmann, F. (2016). False positives and false negatives in functional near-infrared spectroscopy: Issues, challenges, and the way forward. *Neurophotonics, 3*(3), Article 031405. https://doi.org/10.1117/1.NPh.3.3.031405

Tadel, F., Baillet, S., Mosher, J. C., Pantazis, D., & Leahy, R. M. (2011). Brainstorm: A User-Friendly Application for MEG/EEG Analysis. *Computational Intelligence and Neuroscience, 2011*, 1–13. https://doi.org/10.1155/2011/879716

Tak, S., Kempny, A. M., Friston, K. J., Leff, A. P., & Penny, W. D. (2015). Dynamic causal modelling for functional near-infrared spectroscopy. *NeuroImage, 111*, 338–349. https://doi.org/10.1016/j.neuroimage.2015.02.035

Tak, S., & Ye, J. C. (2014). Statistical analysis of fNIRS data: A comprehensive review. *NeuroImage, 85*, 72–91. https://doi.org/10.1016/j.neuroimage.2013.06.016

Tarr, B., Launay, J., & Dunbar, R. I. M. (2014). Music and social bonding: "Self-other" merging and neurohormonal mechanisms. *Frontiers in Psychology, 5*. https://www.frontiersin.org/articles/10.3389/fpsyg.2014.01096.

Tervaniemi, M. (2023). The neuroscience of music – towards ecological validity. *Trends in Neurosciences, 46*(5), 355–364. https://doi.org/10.1016/j.tins.2023.03.001

Thaut, M. H., Hoemberg, V., Thaut, M. H., & Hoemberg, V. (Eds.). (2016). *Handbook of Neurologic Music Therapy*. Oxford University Press.

Thaut, M. H., McIntosh, G. C., & Hoemberg, V. (2014). Neurologic music therapy: From social science to neuroscience. *Handbook of Neurologic Music Therapy*, 1–6.

Thompson, M. R., & Luck, G. (2012). Exploring relationships between pianists' body movements, their expressive intentions, and structural elements of the music. *Musicae Scientiae, 16*(1), 19–40. https://doi.org/10.1177/1029864911423457

Tillmann, B., Poulin-Charronnat, B., & Bigand, E. (2014). The role of expectation in music: From the score to emotions and the brain. *WIREs Cognitive Science, 5*(1), 105–113. https://doi.org/10.1002/wcs.1262

Toronov, V. Y., Zhang, X., & Webb, A. G. (2007). A spatial and temporal comparison of hemodynamic signals measured using optical and functional magnetic resonance imaging during activation in the human primary visual cortex. *NeuroImage, 34*(3), 1136–1148. https://doi.org/10.1016/j.neuroimage.2006.08.048

Torricelli, A., Contini, D., Pifferi, A., Caffini, M., Re, R., Zucchelli, L., & Spinelli, L. (2014). Time domain functional NIRS imaging for human brain mapping. *NeuroImage, 85*, 28–50. https://doi.org/10.1016/j.neuroimage.2013.05.106

Trehub, S. E. (2019). Nurturing infants with music. *International Journal of Music in Early Childhood, 14*(1), 9–15. https://doi.org/10.1386/ijmec.14.1.9_1

Tsuzuki, D., & Dan, I. (2014). Spatial registration for functional near-infrared spectroscopy: From channel position on the scalp to cortical location in individual and group analyses. *NeuroImage, 85*, 92–103. https://doi.org/10.1016/j.neuroimage.2013.07.025

Tsuzuki, D., Jurcak, V., Singh, A. K., Okamoto, M., Watanabe, E., & Dan, I. (2007). Virtual spatial registration of stand-alone fNIRS data to MNI space. *NeuroImage, 34*(4), 1506–1518. https://doi.org/10.1016/j.neuroimage.2006.10.043

Vanzella, P., Balardin, J. B., Furucho, R. A., Zimeo Morais, G. A., Braun Janzen, T., Sammler, D., & Sato, J. R. (2019). fNIRS Responses in Professional Violinists While Playing Duets: Evidence for Distinct Leader and Follower Roles at the Brain Level. *Frontiers in Psychology, 10*, 164. https://doi.org/10.3389/fpsyg.2019.00164

Villringer, A., & Chance, B. (1997). Non-invasive optical spectroscopy and imaging of human brain function. *Trends in Neurosciences, 20*(10), 435–442. https://doi.org/10.1016/S0166-2236(97)01132-6

Vuust, P., Heggli, O. A., Friston, K. J., & Kringelbach, M. L. (2022). Music in the brain. *Nature Reviews Neuroscience, 23*(5), 287–305. https://doi.org/10.1038/s41583-022-00578-5

Wakita, M. (2014). Broca's area processes the hierarchical organization of observed action. *Frontiers in Human Neuroscience*, (JAN), 937. https://doi.org/10.3389/FNHUM.2013.00937

Wan, C. Y., & Schlaug, G. (2010). Music Making as a Tool for Promoting Brain Plasticity across the Life Span. *The Neuroscientist, 16*(5), 566–577. https://doi.org/10.1177/1073858410377805

Wang, Q., Zhu, G.-P., Yi, L., Cui, X.-X., Wang, H., Wei, R.-Y., & Hu, B.-L. (2020). A Review of Functional Near-Infrared Spectroscopy Studies of Motor and Cognitive Function in Preterm Infants. *Neuroscience Bulletin, 36*(3), 321–329. https://doi.org/10.1007/s12264-019-00441-1

Wang, Z., Liao, M., Li, Q., Zhang, Y., Liu, H., Fan, Z., & Bu, L. (2020). Effects of three different rehabilitation games' interaction on brain activation using functional near-infrared spectroscopy. *Physiological Measurement, 41*(12), Article 125005. https://doi.org/10.1088/1361-6579/abcd1f

Wijeakumar, S., Kumar, A., Delgado Reyes, L. M., Tiwari, M., & Spencer, J. P. (2019). Early adversity in rural India impacts the brain networks underlying visual working memory. *Developmental Science, 22*(5), e12822.

Wolf, M., Ferrari, M., & Quaresima, V. (2007). Progress of near-infrared spectroscopy and topography for brain and muscle clinical applications. *Journal of Biomedical Optics, 12*(6), Article 062104. https://doi.org/10.1117/1.2804899

Wollman, I., Penhune, V., Segado, M., Carpentier, T., & Zatorre, R. J. (2018). Neural network retuning and neural predictors of learning success associated with cello training. *Proceedings of the National Academy of Sciences, 115*(26). https://doi.org/10.1073/pnas.1721414115

Xu, J., Liu, X., Zhang, J., Li, Z., Wang, X., Fang, F., & Niu, H. (2015). FC-NIRS: A Functional Connectivity Analysis Tool for Near-Infrared Spectroscopy Data. *BioMed Research International, 2015*, 1–11. https://doi.org/10.1155/2015/248724

Yamada, Y., & Ono, Y. (2019). Detection of Music Preferences using Cerebral Blood Flow Signals. In *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 490–493). https://doi.org/10.1109/EMBC.2019.8856351

Ye, J., Tak, S., Jang, K., Jung, J., & Jang, J. (2009). NIRS-SPM: Statistical parametric mapping for near-infrared spectroscopy. *NeuroImage, 44*(2), 428–447. https://doi.org/10.1016/j.neuroimage.2008.08.036

Yoo, S.-H., Santosa, H., Kim, C.-S., & Hong, K.-S. (2021). Decoding Multiple Sound-Categories in the Auditory Cortex by Neural Networks: An fNIRS Study. *Frontiers in Human Neuroscience*, 211. https://doi.org/10.3389/FNHUM.2021.636191

Yücel, M. A., Lühmann, A. V., Scholkmann, F., Gervain, J., Dan, I., Ayaz, H., Boas, D., Cooper, R. J., Culver, J., Elwell, C. E., Eggebrecht, A., Franceschini, M. A., Grova, C., Homae, F., Lesage, F., Obrig, H., Tachtsidis, I., Tak, S., Tong, Y., & Wolf, M. (2021). Best practices for fNIRS publications. *Neurophotonics, 8*(01). https://doi.org/10.1117/1.NPh.8.1.012101

Yücel, M. A., Selb, J., Aasted, C. M., Petkov, M. P., Becerra, L., Borsook, D., & Boas, D. A. (2015). Short separation regression improves statistical significance and better localizes the hemodynamic response obtained by near-infrared spectroscopy for tasks with differing autonomic responses. *Neurophotonics, 2*(3), Article 035005. https://doi.org/10.1117/1.NPh.2.3.035005

Yücel, M. A., Selb, J. J., Huppert, T. J., Franceschini, M. A., & Boas, D. A. (2017). Functional Near Infrared Spectroscopy: Enabling routine functional brain imaging. *Current Opinion in Biomedical Engineering, 4*, 78–86. https://doi.org/10.1016/j.cobme.2017.09.011

Yuksel, B. F., Oleson, K. B., Harrison, L., Peck, E. M., Afergan, D., Chang, R., & Jacob, R. J. K. (2016). Learn piano with BACh: An adaptive learning interface that adjusts task difficulty based on brain state. *Conference on Human Factors in Computing Systems - Proceedings, 5372–5384*. https://doi.org/10.1145/2858036.2858388

Zatorre, R. J. (2005). Music, the food of neuroscience? *Nature, 434*(7031), 312–315. https://doi.org/10.1038/434312a

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory–motor interactions in music perception and production. *Nature Reviews Neuroscience, 8*(7), 547–558. https://doi.org/10.1038/nrn2152

Zatorre, R. J., & Salimpoor, V. N. (2013). From perception to pleasure: Music and its neural substrates. *Proceedings of the National Academy of Sciences*, *110*(supplement_2), 10430–10437. doi: 10.1073/pnas.1301228110.

Zhang, X., Noah, J. A., Dravida, S., & Hirsch, J. (2020). Optimization of wavelet coherence analysis as a measure of neural synchrony during hyperscanning using functional near-infrared spectroscopy. *Neurophotonics, 7*(1), Article 015010. https://doi.org/10.1117/1.NPh.7.1.015010

Zhao, H., & Cooper, R. J. (2017). Review of recent progress toward a fiberless, whole-scalp diffuse optical tomography system. *Neurophotonics, 5*(01), 1. https://doi.org/10.1117/1.NPh.5.1.011012

Zimeo Morais, G. A., Balardin, J. B., & Sato, J. R. (2018). fNIRS Optodes' Location Decider (fOLD): A toolbox for probe arrangement guided by brain regions-of-interest. *Scientific Reports, 8*(1), 3341. https://doi.org/10.1038/s41598-018-21716-z

Zinos, A., Wagner, J. C., Beardsley, S. A., Chen, W.-L., Conant, L., Malloy, M., Heffernan, J., Quirk, B., Prost, R., Maheshwari, M., Sugar, J., & Whelan, H. T. (2024). Spatial correspondence of cortical activity measured with whole head fNIRS and fMRI: Toward clinical use within subject. *NeuroImage, 290*, Article 120569. https://doi.org/10.1016/j.neuroimage.2024.120569