

The speed limit of dynamic and real-time synchrony imaging in fNIRS

Katarina Lodrant ¹, Dimitri Van De Ville ^{2,3}, Frank Scharnowski ¹, Kathrin Kostorz ¹

¹ *Department of Cognition, Emotion, and Methods in Psychology, Faculty of Psychology, University of Vienna, Vienna, Austria*

² *Neuro-X Institute, École Polytechnique Fédérale de Lausanne, Geneva, Switzerland*

³ *Department of Radiology and Medical Informatics, University of Geneva, Geneva, Switzerland*

Introduction

Interpersonal neural synchrony (INS), the temporal alignment of neural activity across individuals, is a central construct in social neuroscience, and functional near-infrared spectroscopy (fNIRS) is now the dominant hyperscanning modality (Hakim et al., 2023). Estimating INS in real time opens a range of applications, notably several forms of synchrony neurofeedback: mutual hyperfeedback, in which two interacting people are shown their shared synchrony; unidirectional feedback, in which one person aligns to a partner's live signal; and template-based feedback, in which a signal is aligned to a fixed, pre-recorded time course such as an expert's. All rest on the same online estimate of synchrony, typically wavelet transform coherence (WTC; Cui et al., 2012) in fNIRS INS research. Its time–frequency assumptions are rarely made explicit, yet they set a hard limit on how fast synchrony can be tracked. We ask how these signal-processing properties constrain dynamic and real-time INS imaging using fNIRS.

Methods

We introduce the fundamental principles of time–frequency analysis relevant to dynamic INS estimation in fNIRS and illustrate their practical implications. We discuss the signal-processing concepts that determine the temporal resolution of wavelet-based synchrony measures, in particular WTC. This includes the time–frequency uncertainty principle, the wavelet transform as a frequency-selective detector, and the cone of influence. Using representative fNIRS frequency bands as worked examples, we derive the minimum analysis windows required for reliable synchrony estimation and describe how wavelet properties, edge effects, and preprocessing choices constrain temporal resolution. Based on this analysis, we formulate practical recommendations for dynamic and real-time INS applications, including synchrony neurofeedback.

Results

Interpretable neural synchrony in fNIRS is confined to a narrow low-frequency band (~ 0.01 – 0.09 Hz), which already limits how quickly an estimate can be updated. Within it, the frequency of interest determines the achievable temporal resolution: resolving lower frequencies requires longer analysis windows. Because of the uncertainty relation, the resulting cone of influence must be excluded at every window edge. Therefore, the temporal resolution of a dynamic synchrony estimate is limited to roughly twice the wavelet's e-folding time, around one minute, or even coarser at the low end of the frequency band (Kostorz et al., 2025). This floor is set by the transform itself, not by the estimator or hardware, and applies to all synchrony metrics. The frequency of interest should therefore be chosen to balance temporal resolution against spectral specificity according to the demands of each application. Caution should be paid to additional filtering, as it may introduce additional phase shifting and temporal spread; short-channel regression should be preferred.

Conclusions

Time–frequency uncertainty sets the speed limit for real-time synchrony imaging in fNIRS: it determines the achievable temporal resolution and, hence, the responsiveness of dynamic INS estimates and INS neurofeedback. For feedback setups, we therefore recommend intermittent rather than continuous neurofeedback.

References

1. Hakim, U., Gjorgjieva, T., et al. (2023). Quantification of inter-brain coupling: A review of current analytic methods and their applicability to hyperscanning. *NeuroImage*, 280, 120354.

2. Cui, X., Bryant, D. M., & Reiss, A. L. (2012). NIRS-based hyperscanning reveals increased interpersonal coherence in superior frontal cortex during cooperation. *NeuroImage*, 59(3), 2430–2437.
4. Kistorz, K., Nguyen, T., Pan, Y., Melinscak, F., Steyrl, D., Hu, Y., Sorger, B., Hoehl, S., & Scharnowski, F. (2025). Investigating short windows of interbrain synchrony: A step toward fNIRS-based hyperfeedback. *Imaging Neuroscience*, 3, IMAG.a.43.
3. Lodrant, K., Van De Ville, D., Scharnowski, F., & Kistorz, K. (2026). Interbrain synchrony analysis for fNIRS – a signal processing primer. *PsyArXiv*