Correction for time-varying signal power in fNIRS connectivity analyses

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Introduction

- FNIRS signals are contaminated by non-stationary physiological noise and motion artefacts.
- Non-stationary fNIRS signals violate the stationarity assumption in resting-state functional connectivity (RSFC) measures, invalidating statistical significance tests.
- We empirically establish the non-stationarity of fNIRS signals and propose a simple correction for the time-varying signal power of fNIRS signals, drawn from a similar method proposed for fMRI [1].
- Our correction restores the integrity of RSFC analyses.

Theory

- Neurovascular effects can affect both neuronal and physiological components of fNIRS signals.
- A multiplicative signal model is used $x_t = \sqrt{q_t} \cdot x_{s,t}$, where x_t and $x_{s,t}$ denote the observed non-stationary fNIRS signal and the underlying stationary signal respectively. q_t represents time-varying signal power.
- The non-stationary signal pair, x_t and y_t, of length T, with true correlation ρ, follow signal model,

$$x_t = \sqrt{q_t} \cdot x_{s,t}\,, \qquad y_t = \sqrt{q_t} \cdot y_{s,t}\,.$$

- Sample correlation between stationary signals has variance

$$\mathrm{var}\left(\mathrm{corr}(x_{s,t}, y_{s,t})\right) \approx \frac{1-\rho^2}{T-2}.$$

- Variance of sample correlation between non-stationary signal pairs

$$\mathrm{var}\left(\mathrm{corr}(x_t, y_t)\right) \approx \frac{\frac{\overline{q^2}}{(\bar{q})^2} - \rho^2}{T-2},$$

where $\overline{q^2}$ and $\bar{q}$ represent the mean values for q_t^2 and q_t.

- Jensen's inequality $\mathrm{var}\left(\mathrm{corr}(x_t, y_t)\right) \geq \mathrm{var}\left(\mathrm{corr}(x_{s,t}, y_{s,t})\right)$.
- Time-varying signal power increases the variance of sample correlation, invalidating tests of statistical significance.

The Correction

- Non-stationary signal power can be estimated using signal ensemble variance, denoted $\hat{q}_t$.
- We propose a correction for non-stationary signal power used in fNIRS signals $x_{c,t} = x_t / \hat{q}_t$.

Method

- Non-stationarity of fNIRS signals is illustrated using signal intensities (1A) and channel variance (1B).

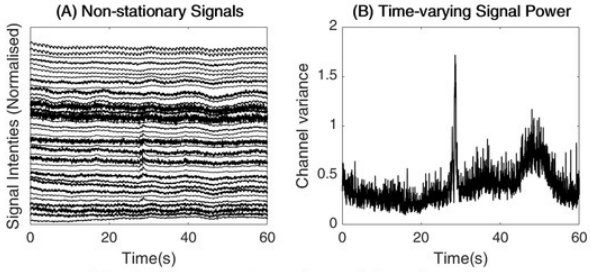

Fig 1. Non-stationarity of the signals

- The impact of time-varying power on correlation was assessed using simulation and experimental data.
- White Gaussian signal pairs with a true correlation of 0.2 were scaled by non-stationary power, generated from an Inverse Gamma distribution.
- Distributions of sample correlation for stationary signals, signals with time-varying signal power and corrected signals are illustrated.
- Experimental fNIRS data were obtained from an open-access dataset [2]. RSFC estimates were calculated before and after correction using Fisher's z-scores, adjusted for non-white frequency spectra [3].

Results

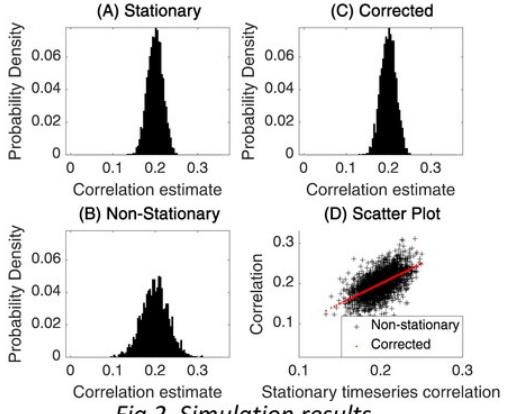

Fig 2. Simulation results

Results

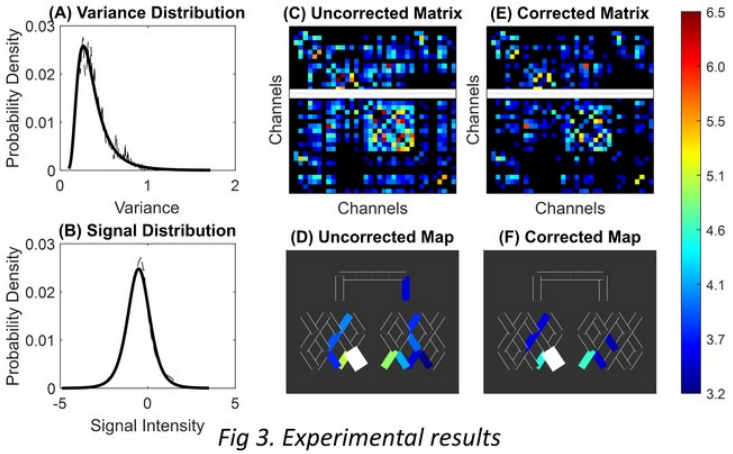

Fig 3. Experimental results

- Simulation results show non-stationary signal power increases the variance of z-score (2A,2B).
- After applying our correction, the distribution of sample correlation is restored to that of stationary signals (2A,2C).
- Experimental results show time-varying variance and signal intensities are optimally fit with an Inverse Gamma distribution (3A) and a Student's *t*-distribution (3B).
- The decreases in z-scores in connectivity results (3C-3F) show the ability of the correction method to generate connectivity results consistent with that expected from fNIRS resting state data.

Conclusions

- Non-stationary fNIRS signals violate the stationarity assumption in RSFC, invalidating statistical results.
- We propose a correction to remove the impact of time-varying signal power, restoring stationarity of the fNIRS signals.

References

[1] Davey, C. E., Grayden, D. B., & Johnston, L. A. (2021). Correcting for Non-stationarity in BOLD-fMRI Connectivity Analyses. *Frontiers in neuroscience*, *15*, 157.

[2] Jahani, S., Setarehdan, S. K., Boas, D. A., & Yücel, M. A. (2018). Motion artifact detection and correction in functional near-infrared spectroscopy: a new hybrid method based on spline interpolation method and Savitzky–Golay filtering. *Neurophotonics*, 5(1), 015003.

[3] Wang, M., Davey, C. E., & Johnston, L. A. (2021). Correction of induced functional connectivity in filtered resting state fNIRS data. In *25th Annual Meeting of the Organization for Human Brain Mapping (OHBM)*.