Speckle contrast analysis in parallel interferometric near-infrared spectroscopy for cerebral blood flow monitoring

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1. Introduction

We present interferometric speckle contrast optical spectroscopy (iSCOS) — a novel approach for real-time, non-invasive monitoring of cerebral blood flow (CBF) during prefrontal activation induced by cognitive stimuli. Unlike conventional diffuse correlation spectroscopy (DCS) that requires ultra-fast detectors, iSCOS leverages spatial speckle contrast analysis, enabling high parallelization with standard 2D imaging sensors, while operating in continuous-wave (CW) mode.

The system employs a Mach-Zehnder interferometric configuration using multi-mode optical fibers to deliver and collect light. The reference and sample beams are recombined, and the resulting interference patterns are captured by a high-speed CMOS camera. Speckle contrast is computed through digital multi-exposure synthesis, allowing robust estimation of blood flow dynamics without the need for expensive single-photon detectors.

2. Methods and results

We validated the system performance in liquid phantoms with controlled scattering properties (μs' = 7.5–12.5 cm^{-1}), systematically analyzing speckle contrast and autocorrelation functions across various source-detector separations and integration times. The speckle contrast exhibited superior stability and noise robustness compared to autocorrelation, particularly at larger separations and lower photon counts.

For in vivo evaluation, we monitored prefrontal cortex activation in a healthy volunteer during a reading task. The relative blood flow index increased by ~14% based on autocorrelation analysis and by ~32% using speckle contrast analysis, consistent with prior SPAD-based DCS measurements. Notably, the integration time required for iSCOS was ~10× shorter than conventional methods, demonstrating its efficiency in dynamic hemodynamic monitoring.

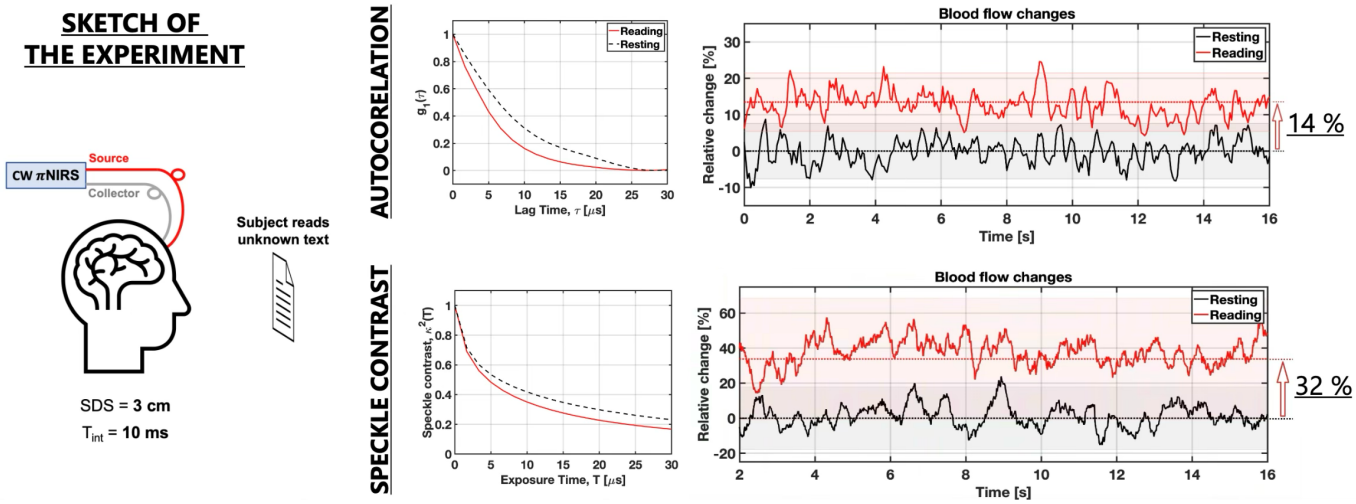

Fig. 1. Fig. 10. In vivo monitoring of prefrontal cortex activation using interferometric speckle contrast optical spectroscopy (iSCOS). Relative changes in cerebral blood flow index (rBFI) were measured during a reading task compared to a resting baseline. The top panel presents results derived from autocorrelation analysis, while the bottom panel displays corresponding changes estimated via speckle contrast analysis. Both methods captured a task-evoked increase in rBFI, with the speckle contrast approach demonstrating enhanced sensitivity to hemodynamic fluctuations.

Our findings demonstrate that iSCOS enables fast, cost-effective, and scalable CBF monitoring, offering a promising tool for functional neuroimaging in affective neuroscience, psychiatric research, and clinical neuroergonomics.

3. References

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