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Scalp-based parcellation for longitudinal fNIRS studies

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Abstract: Functional near infrared spectroscopy (fNIRS) delivers a flexible, portable, and wearable technique for monitoring brain function in situations where fMRI is not feasible, not suitable, or inaccessible. However, variations in optode locations and head shapes and sizes throughout development lead to considerable challenges in group-based and longitudinal studies that generally use either channel-focused analyses or image reconstruction techniques that require strong participant-atlas correspondence. We present a scalp-based parcellation technique that compensates for variation in optode array placement and general head morphology and accounts for fNIRS spatial sampling with minimal assumptions about the underlying head and brain structure to support robust statistical analyses.

Introduction

Functional near infrared spectroscopy (fNIRS) provides an alternative to functional magnetic resonance imaging (fMRI) for studying brain function in settings where fMRI is not feasible or is inaccessible [1-3]. However, channel-based fNIRS techniques require consistent array positions and scalp-cortex correspondences; and full reconstruction-based methods need participant-specific structural MRI for precise anatomical co-registration [4, 5]. Here we propose a parcellation technique that provides a scalp-based method for co-registration using age-appropriate anatomical atlases. The proposed method projects the estimated fNIRS measurement sensitivity onto the parcels using the optode array location from the imaging session. Our approach delivers a flexible and robust method for increasing power in fNIRS studies by aligning optode array location and parcel sensitivity across subjects for multiple channels without individual structural MRI.

Methods

The proposed technique was assessed using array placement data from 393 participants divided into 6-, 24-, and 36-month-old (mo) cohorts (n=137,143,113, respectively). We registered the participant optode locations to the atlas 10-20 coordinate system and calculated the median absolute deviation, mean distance from the median array location, and the standard deviation from the median array location to assess positional variability (**Fig 1**).

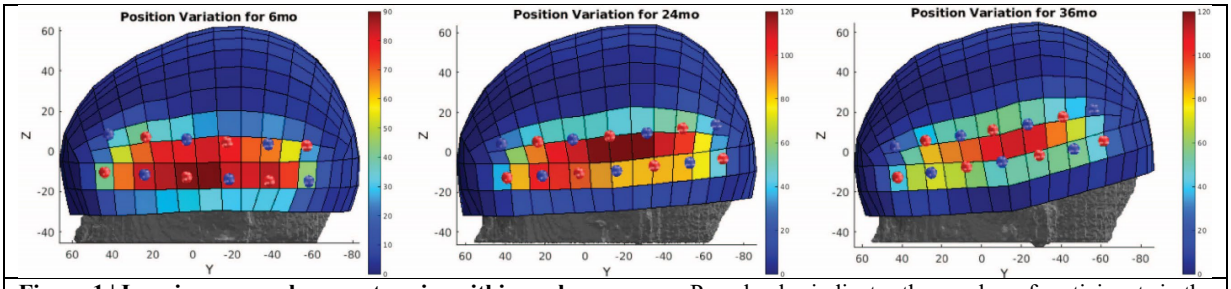

Figure 1 | Imaging array placement varies within each age group. Parcel color indicates the number of participants in the age group with significant array coverage for that given parcel. The median array placement is displayed with red (sources) and blue (detectors) spheres.

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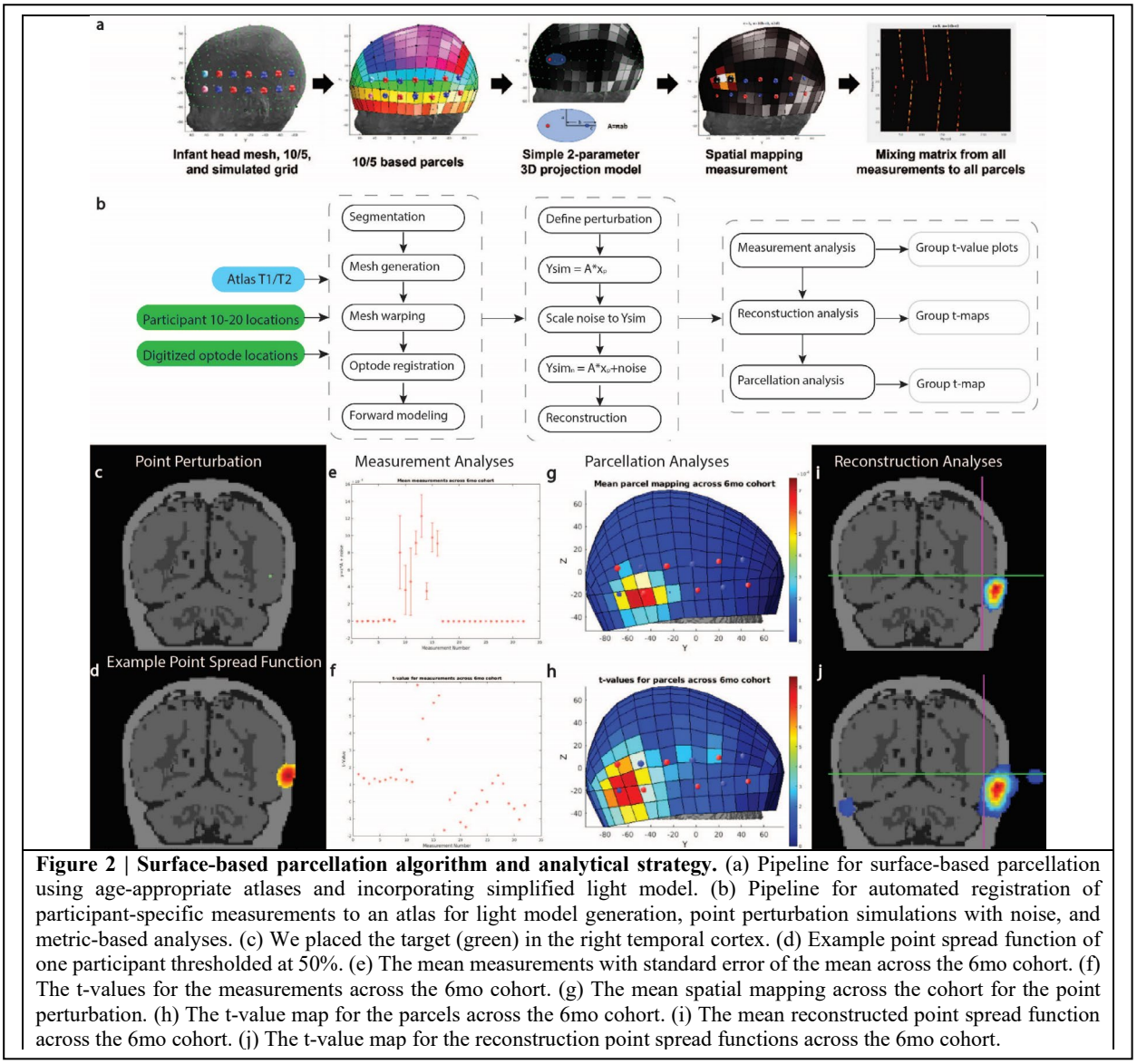

Figure 2 | Surface-based parcellation algorithm and analytical strategy. (a) Pipeline for surface-based parcellation using age-appropriate atlases and incorporating simplified light model. (b) Pipeline for automated registration of participant-specific measurements to an atlas for light model generation, point perturbation simulations with noise, and metric-based analyses. (c) We placed the target (green) in the right temporal cortex. (d) Example point spread function of one participant thresholded at 50%. (e) The mean measurements with standard error of the mean across the 6mo cohort. (f) The t-values for the measurements across the 6mo cohort. (g) The mean spatial mapping across the cohort for the point perturbation. (h) The t-value map for the parcels across the 6mo cohort. (i) The mean reconstructed point spread function across the 6mo cohort. (j) The t-value map for the reconstruction point spread functions across the 6mo cohort.

The parcellation method samples the scalp surface using a regular quadrilateral array based on the international 10/5 system on age-appropriate atlases [6]. We incorporated an elliptical light model between source-detector pairs, where the major axis relies on the source-detector distance and a tunable distance from the optode to the edge of the ellipse and the minor axis is tunable for optimized model performance, that is projected onto the parcels and determines the spatial mapping for each measurement. The parcellation procedure maps the individual fNIRS channels to parcels containing variable contributions from multiple channels (**Fig 2a**). To compare the proposed method to established analysis techniques, we simulated a point perturbation in μ_a at 850nm approximately 7mm below the cortical surface (**Fig 2c**). We modeled the optical density for all measurements as $y=A*x+noise$ where y is the optical density, A refers to the sensitivity matrix, and x represents the simulated point perturbation data [7] (**Fig 2b**). The measurement-based analyses used these simulated measurements, Y, to calculate the t-value across each age group. The parcellation strategy incorporated the mixing matrices M, calculated for each participant, with the simulated measurements Y to calculate the spatial mapping in each parcel as $P=MY$, and then calculated t-values for each cohort. The reconstruction analyses incorporated the full reconstruction into the voxelated space such that $x_{recon}=A\text{-}1(A*x\text{-}noise)$ calculates the point spread function for each participant. Then, the group-wise values were calculated

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across each cohort. We removed 4 participants from simulation analyses in the 6mo cohort because the cap placement did not cover the perturbation location and analyzed the remaining 133 participants. All participants in the 24mo and 36mo cohorts were included in the simulation analyses.

Table 1. Maximum t-value for each age group and analysis technique

Method	6mo Max t-Value	24mo Max t-Value	36mo Max t-Value
Measurement	13.14	12.40	8.49
Parcellation	20.96	17.94	13.67
Reconstruction	31.76	37.01	23.37

Results

Following registration to the normalized atlas 10-20 coordinate system, optode placements within the age groups had median absolute deviations of 6.6, 5.15, and 7.29mm with mean(std) distance from the median array location of 7.45(4.44), 5.95(3.62), and 8.31(5.20)mm for the 6, 24, and 36mo cohorts, respectively. To establish the benefit of scalp-based parcellation, we calculated the t-values for each analysis metric to compare the variability within the data for the different analytic techniques (**Fig 2c-j**). The reconstruction-based analyses delivered the highest maximum t-values across all age groups with values of 31.76, 37.01, and 23.37 for the 6, 24, and 36mo cohorts, respectively (**Table 1**). Additionally, the parcellation-based methods delivered higher t-values (20.96, 17.94, 13.67) than the measurement-based analyses (13.14, 12.4, 8.49) for all age groups.

Discussion & Conclusions

Our results indicate that parcellation-based analyses manage optode placement variability across age groups without requiring the computational power and time of reconstruction-based analyses. The median absolute deviations and mean distances from the median array location highlight the need to manage positional errors during longitudinal studies. Further, the proposed methodology does not require participant-specific structural imaging like reconstruction-based methods and captures the varied sensitivity differences across the head at both the individual and group levels, even in the presence of outlier cap fits, unlike typical measurement-based analyses. Additionally, the parcellation technique scales to any optode localization technique, such as photogrammetric optode localization with video, on condition that the optode localization algorithm provides 3D coordinates as inputs to the parcellation pipeline.

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