A functionally time-resolved reconstruction technique for high-resolution fMRI.

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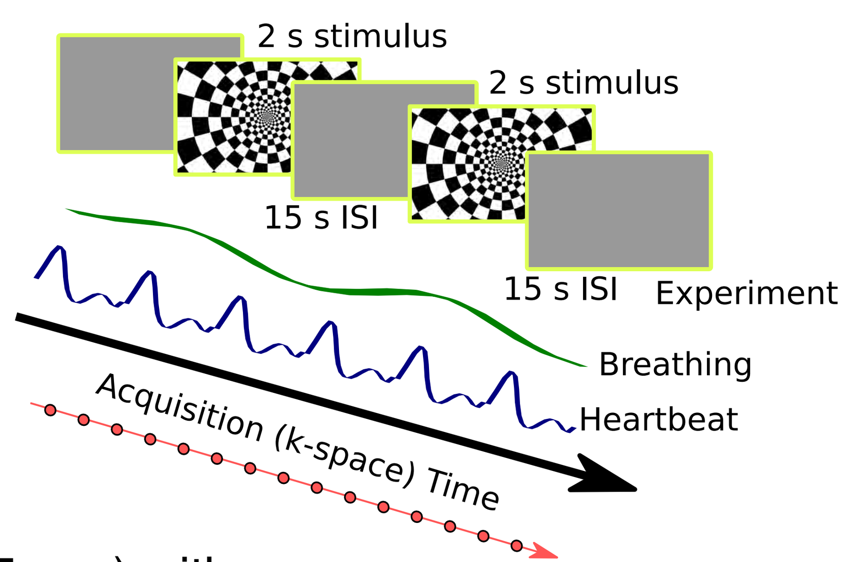
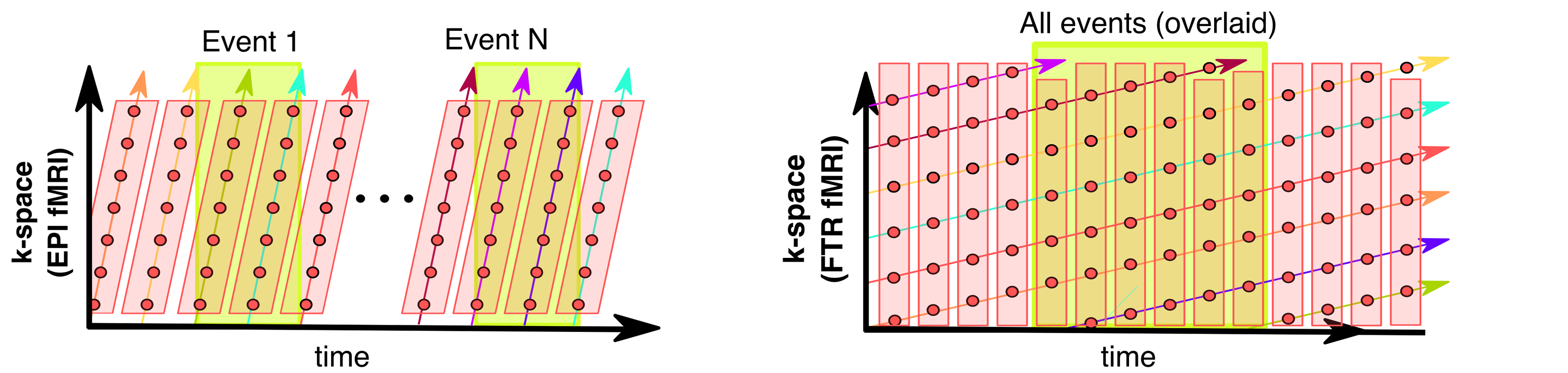
Introduction

- High resolution fMRI is a promising method to probe mesoscopic brain responses[1,2], yet is currently too coarse to sample from individual human columns and layers.
- High-resolution fMRI using EPI readouts and BOLD contrast suffer from spatial distortions and T_2^* blurring due to long readout trains[3].
- Here, we build on time resolved methods[4,5] to incorporate neuroscientific experimental designs and physiological confounds into fMRI reconstruction to time resolve data from multi-echo, multi-shot gradient echo sequences (one k-space line to minimize readout time).
- Our method, ***functionally time-resolved fMRI*** (fTR), of very high spatial resolution (here, up to 0.5 mm) with multiple (6) echoes without sacrificing temporal resolution (here, 0.5 s).

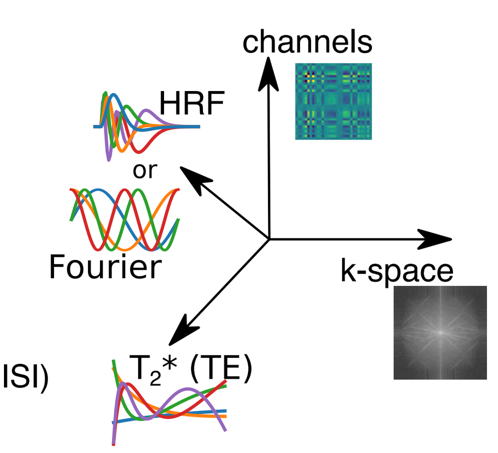




Right (upper): Experimental and k-space acquisition timelines are shown as concurrent processes affecting MRI image formation. **Left:** In a typical fMRI experiment, k-space is sampled (colored arrows) as quickly as possible to form multiple images (red boxes) that form an image time course. Thus reconstruction timelines are anchored to the beginning of the experiment. **Right (lower):** In *functionally time-resolved imaging*, all experimental events are overlaid (green box) in order to fill k-space with a slower (but high-resolution) trajectory. This means that k-space data for each reconstructed image come from different times in the experiment, but reconstructed timelines are anchored to neuronal and physiological events of interest.

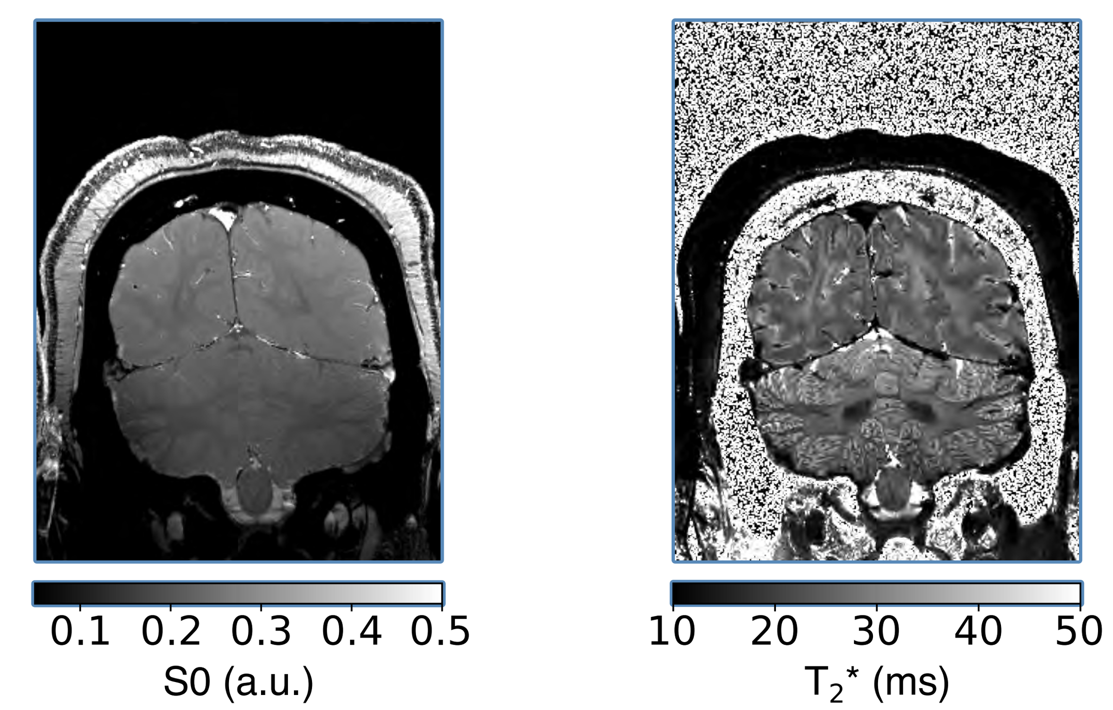
Methods

- **Acquisition:** Five subjects' data were collected on a Siemens MAGNETOM 7T+ w/ Nova 32Rx head coil. We collected two different sequences to demonstrate the utility of fTR-MRI: 1) a 2D GRE sequence (TR=31 ms, TEs=[4.22, 8.38, 12.54, 16.7, 20.86, 25.02] ms (bipolar readout), res=0.5x0.5 mm, slc thickness=0.8 mm, matrix=360x270, PE=R/L, repetitions=36, no acceleration or Partial Fourier, acquisition time=5:01). Prescription was perpendicular to the Calcarine Suclus. 2) a whole brain 3D GRE sequence (TR=4.5 ms, TE=2.1 ms, res=2.0 mm isotropic, FOV=216x220x88 mm, PE=A/P, repetitions=70).
- **Reconstruction:** Data were reconstructed via low-rank tensor completion[4,7] with modes for k-space, receivers, echoes and response time. Initial k-space, channel and echo subspaces were derived non-time resolved data with SVD. The time subspace was either an informed 2-gamma HRF basis (with derivatives; experimental mapping), or an order-2 Fourier basis (physio mapping). The subspaces and rank-(20, 7, 3, 5) core tensor were then iteratively updated with available data until the 2-norm of the core converged.

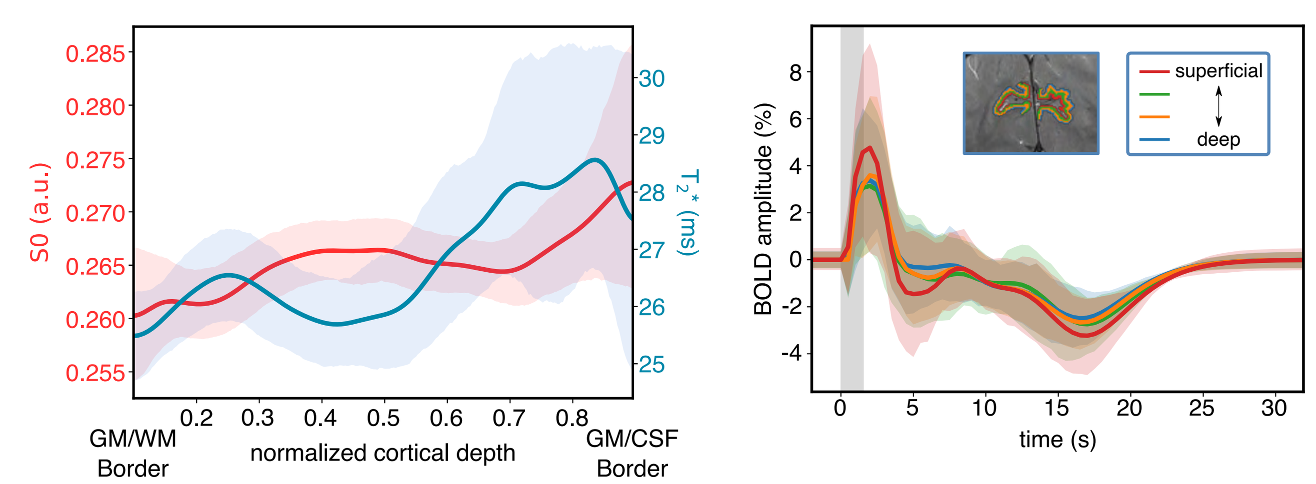


- **Experiment:** Participants were presented a flashing radial checkerboard (10 Hz; 2 s presentation, 15 s ISI) and were asked to fixate for the entire experiment.
- **Analysis:** S0 & T2* maps were linearly fit to log-multi-echo data. These maps were used to segment gray matter of the Calcarine sulcul region and to compute cortical depth values for each voxel (to plot layerwise S0/T2* values) and 4 equivolume layers (to plot response functions) using LAYNII software[8]. 95% confidence intervals for S0/T2* values were computed via 1000 bootstrap samples (33% of voxels in each sample) of layer profiles. CIs for response functions represent the 95% bounds of individual voxel responses.

Results (Task Mapping)



Reconstructed images. Multi-echo data are used to fit high-resolution (0.5 mm) S0 and T_2^* decay time parameters. **Left:** S0 images display good gray/white matter and CSF contrast, enabling segmentation of functional data. **Right:** T_2^* images provide additional CSF and vascular contrast, as well as identification of striate cortex based on the visible Stria of Gennari.

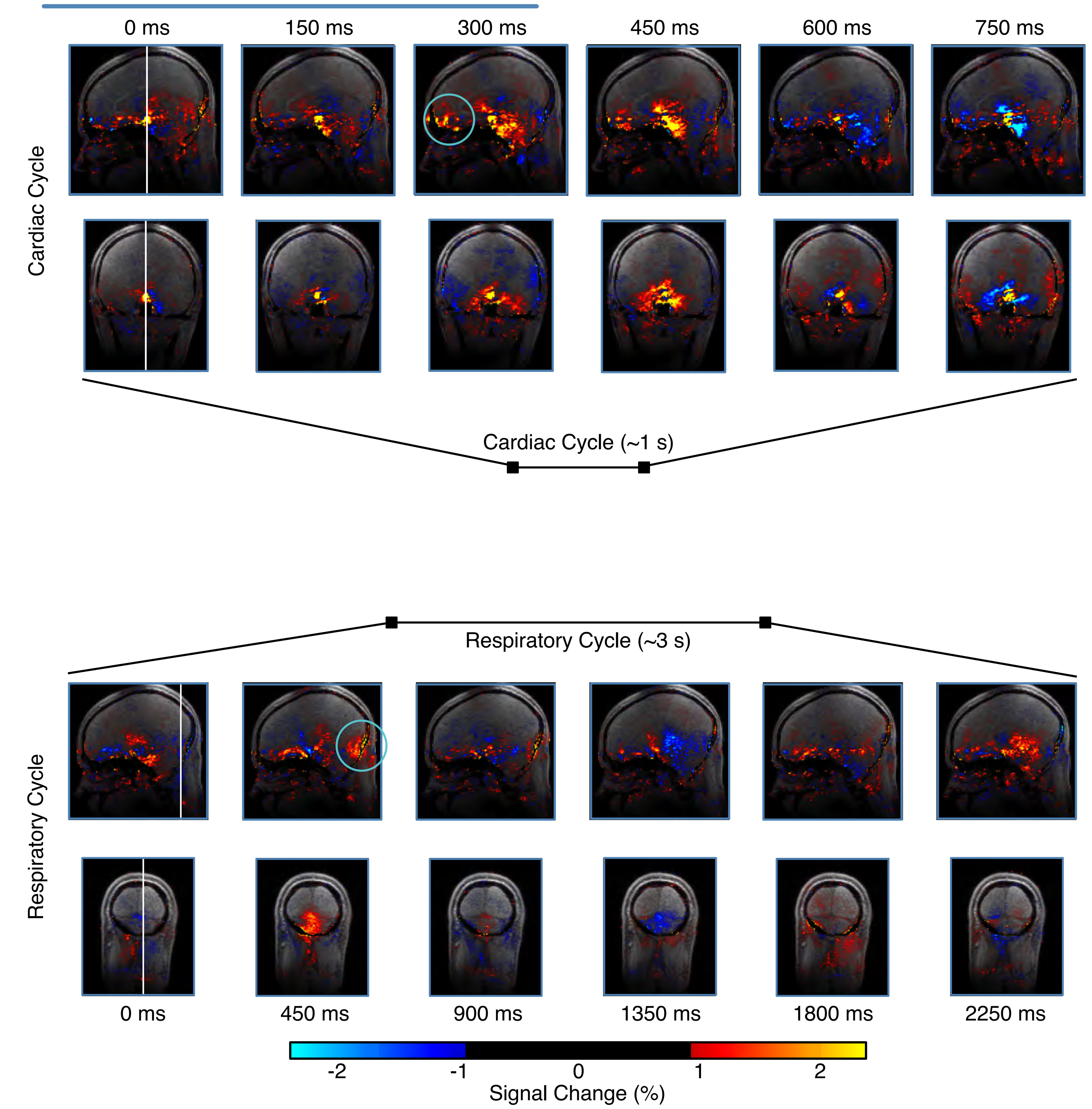


Laminar analyses. Left: Anatomical S0 and T_2^* values are plotted against normalized cortical depth values in the calcarine sulcus (see segmentation image on right). Shaded areas indicate 95% CIs on the mean laminar profile. T_2^* display a characteristic dip in middle layers of striate cortex. **Right:** Functional BOLD responses (optimally combined echo data) to a 2-second flashing checkerboard stimulus (10 Hz) are shown for 4 cortical depth ROIs (see inset segmentation). The gray area indicates stimulation period and shaded colors indicate 95% CIs on individual voxel time courses. Superficial layers (red) show higher response amplitudes and larger undershoots than other cortical depths, similar to high-resolution temporal BOLD profiles seen in rodents[6].

Conclusions

- Functionally time-resolved fMRI incorporates experimental designs and physiology into image reconstruction to capture high spatial and temporal resolution brain responses.
- fTR-fMRI does not suffer from spatial distortions in the phase encoding direction and S0/T2* maps provide good anatomical contrast, aiding neuroscientific interpretation of experimental data.
- Future directions include combining task and physio mapping to better isolate task-related effects from layer fMRI responses.

Results (Physiology Mapping)



Reconstructed physiological cycles. Whole brain MRI data (2 mm isotropic resolution) are resolved over physiological processes. Maps are thresholded to signal changes with magnitudes greater than 1%. **Upper:** A time course of one cardiac cycle (~1 s) is shown. Signal changes are primarily in subcortical areas, as previously reported[9]. The cyan circle highlights additional positive signal changes to the frontal pole during the late systole period. **Lower:** A time course of one respiratory cycle (~3 s). Signal change maps follow susceptibility changes above the frontal sinus; the cyan circle highlights additional changes in occipital cortex and the cerebellum, potentially due to breathing movement.

References

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