Artificial Correlations Induced by SENSE and GRAPPA Corrupt fcMRI Conclusions

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Target Audience: Functional Connectivity and Parallel MR Reconstruction

Background and Purpose: With the increasing popularity of studies that involve non-invasive means of observing functional connectivity within the brain using fcMRI, it is imperative for data acquisition times to be as short as possible. Parallel MRI (pMRI) techniques, such as SENSE[1] and GRAPPA,[2] reconstruct a concurrent acquisition of *k*-space with multiple receiver coils in which lines are omitted in the Phase Encoding direction, decreasing acquisition time. While studies in pMRI revolve around the removal of image artifacts, little to no attention is paid to the statistical implications of these techniques. Not only does a reduced FOV *k*-space have a different covariance structure to a full FOV array, but the processes of unfolding aliased voxels with the SENSE model and the interpolation of missing lines of *k*-space with the GRAPPA model induce correlations between previously aliased voxels and between lines of *k*-space.[3] If the hypothesis assumes no correlation between voxels, it will result in an increase in Type I/II errors in an fcMRI study, depending on the sign of the induced correlation. This study aims to demonstrate the change in the correlation coefficient between previously aliased voxels reconstructed by the SENSE and GRAPPA models by contrast to when *k*-space is fully sampled.

Methods: The MR signal equation in Eq. 1 was used to simulate the acquisition of data in 8 coils, as performed in a standard EPI pulse sequence. For the proton spin density, ρ, a 96×96 Shepp-Logan Phantom was used with a simulated intra-acquisition decay, T_2^*, of 49 and 42 ms for white and grey matter, 2200 ms for CSF, was set to 10^6 ms outside the phantom, and magnetic fields, B, were estimated from experimentally acquired human subject resting-state data by fitting a polynomial to estimated sensitivities. Sub-sampling was simulated by shifting through *k*-space in increments of $R\Delta k$, where the reduction factor was R=2. IID standard Gaussian random noise was added to each of 490 images in both the full and accelerated time series. Using the full FOV data for calibration, the accelerated data was reconstructed with the SENSE and GRAPPA (using a 4×5 2D kernel) models. After reconstruction, spatial filtering was performed with a 2D Hamming window, and voxel time series were convolved with a Hamming bandpass filter to maintain frequencies between 0.01 and 0.08 Hz. Correlations induced by processing and reconstruction were estimated using the techniques outlined in Bruce et al. (2011).[3]

$$f(k_x,k_y,t)=\iint \rho(x,y)e^{-t/T_2^*(x,y)}e^{-i\gamma B(x,y)t}e^{-i2\pi(k_x x+k_y y)}dxdy \qquad (1)$$

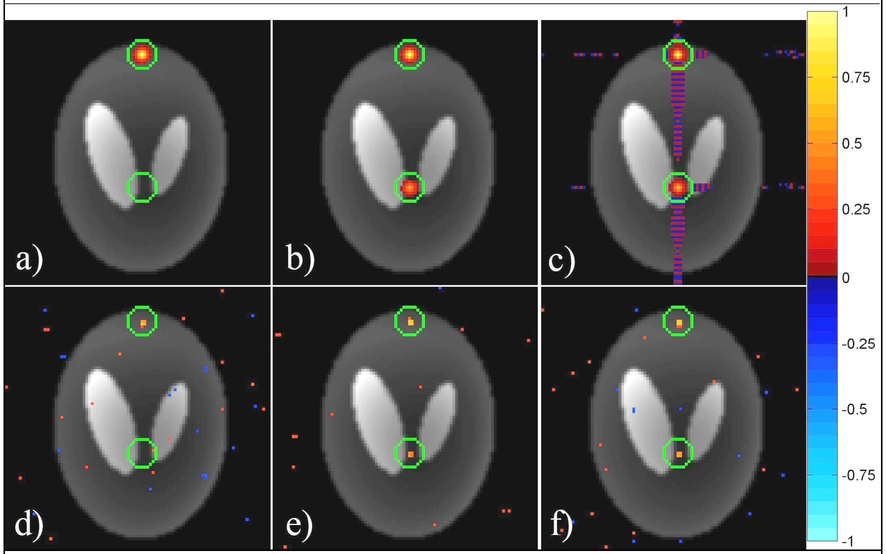

Fig 1: Magnitude squared induced correlations for a) Hamming window, b) SENSE and Hamming, c) GRAPPA and Hamming, along with correlation coefficients for d) fully sampled, e) SENSE reconstructed, and f) GRAPPA reconstructed data. All correlations presented with a threshold of 0.15.

Results & Discussion: For full FOV data, the Hamming window is the only process to induce a correlation, as shown in Fig. 1a about a seed voxel, in the upper green circle, while the correlations about the same voxel for SENSE and GRAPPA reconstructions, combined with the Hamming window, are presented in Figs. 1b and 1c. The correlation coefficient (*cc*) between the seed voxel and all other voxels are presented in Figs. 1d, 1e, and 1f for full FOV, SENSE and GRAPPA reconstructed time series. As expected in Fig. 1d, the fully sampled data does not have a notable *cc* between any other voxel, while the *cc* between the seed voxel and previously aliased voxels, in the lower green circle in the case of SENSE and GRAPPA are not negligible. All correlations in Figs. 1 are of no biological origin, and are aligned with voxels in the commonly investigated Default Mode Network. This could therefore result in Type I/II errors, depending on the sign of the induced correlation and the inherent correlation structure in the acquired data.

Conclusion: The results show that there is in fact a change in the correlation coefficient between previously aliased voxels when using either SENSE or GRAPPA to reconstruct accelerated data. Moreover, these correlations reside in the frequency band commonly associated with fcMRI studies. The change in covariance between previously aliased voxels will arise from a variety of sources, but most notably from the process of un-aliasing reduced FOV images through the pMRI technique employed. While the use of pMRI techniques does provide an attractive means of reducing data acquisition time, it is essential to accounted for the change in covariance is in order to avoid misleading fcMRI conclusions.

References: **1.** KP Pruessmann et al. MRM 42:952-62, 1999. **2.** MA Griswold et al. MRM 47:1202-10, 2002. **3**. IP Bruce et al. MRI 29:1267-87, 2011.

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SYNOPSIS

The reconstruction of sub-sampled spatial frequencies from multiple receiver coils through pMRI techniques such as SENSE (1) and GRAPPA (2) provides an attractive means of increasing the temporal resolution in snapshot image acquisition schemes used in fcMRI. However, most pMRI studies focus on improving the speed and appearance of reconstructed images, while few studies pay attention to the statistical implications that these models impose. In recent studies (3,4), the artificial correlations that the SENSE and GRAPPA models induce between previously aliased voxels were exactly quantified by representing the two models in terms of real-valued linear isomorphisms. As the null hypothesis in fcMRI studies assumes no correlation between voxels, this study illustrates that if the artificial correlations induced by the SENSE and GRAPPA models are not accounted for, they can incur Type I and Type II errors by making voxels appear to be correlated to one another when they are not.

METHODS

DATA ACQUISITION: Data was acquired for a human subject with N_C=8 receiver coils in a 3T GE Signa LX Magnetic Resonance Imager. A collection of 490 full FOV 96 × 96 images were used for both a baseline comparison and for calibration purposes in reconstructing an additional collection of 490 images, sub-sampled by a factor of R=2.

RECONSTRUCTION: For a baseline comparison, the N_C=8 full FOV calibration time series for each coil was combined into a single full FOV time series. After the accelerated data set was reconstructed with both the SENSE and GRAPPA models, all voxel time series were Hamming bandpass filtered to maintain frequencies between 0.009 and 0.08 Hz, after which each image was spatially filtered using a Gaussian kernel with a three voxel FWHM.

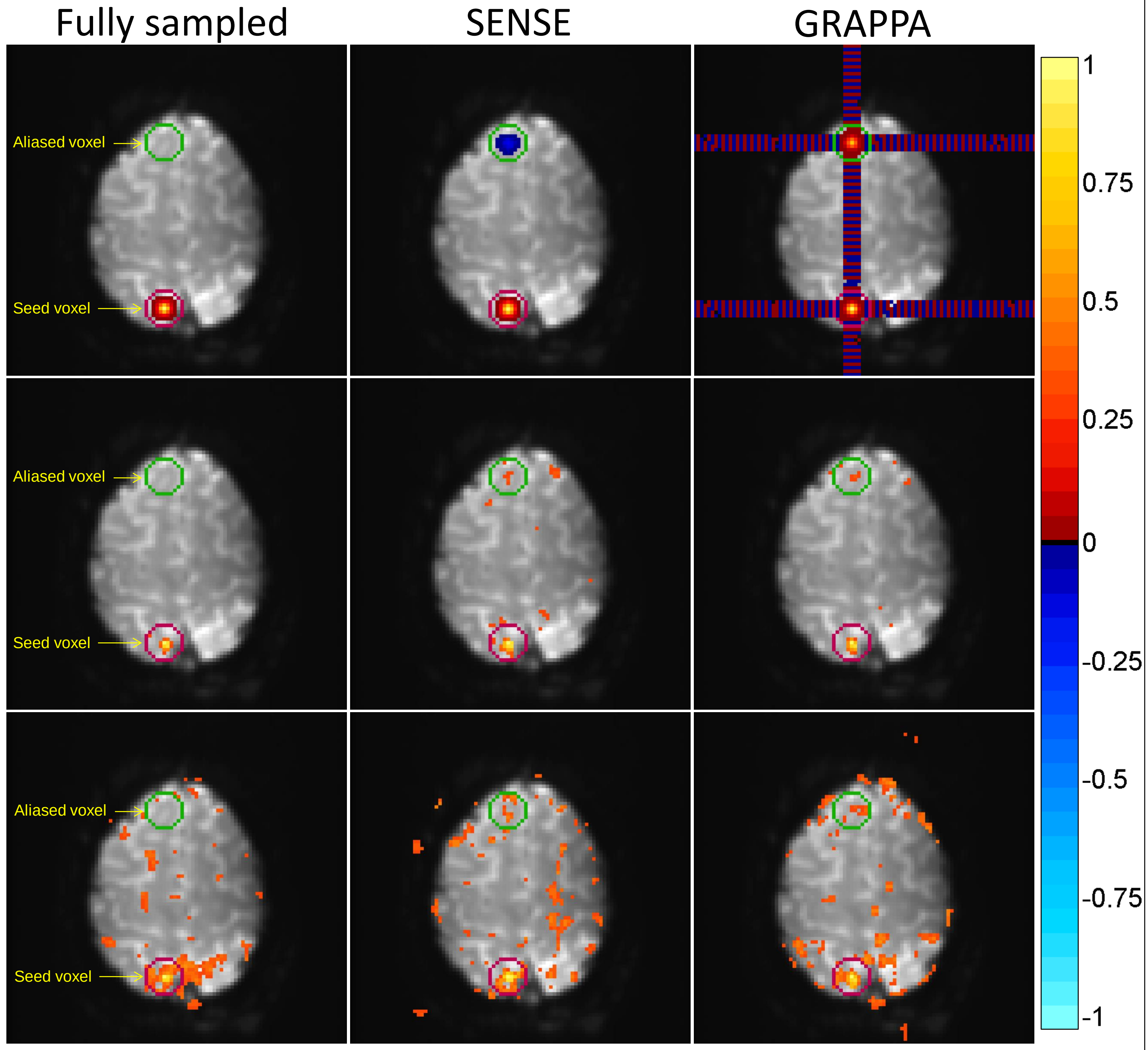
INDUCED CORRELATIONS: For fully sampled data, the only operation performed is the Gaussian spatial filtering process, which can also be represented in matrix form, Sm, to smooth all voxels at once. To observe the correlations induced solely by the SENSE and GRAPPA models, the models are represented in terms of a collection of real-valued permutation and reconstruction matrix operators that reconstruct all aliased voxels at once, O_{SE} and O_G. The covariance and correlations artificially induced into each reconstructed data set solely by reconstruction operations are thus:

Data Set	Induced Covariance	Induced Correlation
Fully sampled	$\Sigma_{full}=SmSm^T$	$\Gamma_{full}=\mathrm{corr}(\Sigma_{full})$
SENSE recon.	$\Sigma_{SE}=SmO_{SE}O_{SE}{}^TSm^T$	$\Gamma_{SE}=\mathrm{corr}(\Sigma_{SE})$
GRAPPA recon.	$\Sigma_G=SmO_GO_G{}^TSm^T$	$\Gamma_G=\mathrm{corr}(\Sigma_G)$

The correlation induced about a voxel by either spatial filtering, the SENSE model or the GRAPPA model is thus determined by reshaping the corresponding row of Γ_{full}, Γ_{SE}, and Γ_G into 96 × 96 matrices.

RESULTS AND DISCUSSION

For fully sampled data, the only operation applied is the Gaussian spatial filtering, which induces no correlation between the seed voxel and a previously aliased voxel in Fig. 1a. Consequently, correlation coefficients (cc) estimated from the full FOV reconstructed time series in Fig. 1b and from the full FOV fcMRI bandpass filtered time series cc's in Fig. 1c also exhibit no correlation between the seed and aliased voxels. For SENSE and GRAPPA, the model induced correlations, Γ_{SE} and Γ_G, in Fig. 1a exhibit a non-zero correlation between previously aliased voxels, and thus the time series cc's in Fig. 1b and bandpass filtered fcMRI cc's in Fig 1c. in turn exhibit correlations between the seed and previously aliased voxels that exceed a threshold of 0.35.



a) Magnitude^2 model induced correlations, Γ TH=10^{-5}

b) Magnitude^2 time series estimated cc's TH=0.35

c) Magnitude^2 fcMRI bandpass filtered cc's TH=0.35

Figure 1

As both the SENSE and GRAPPA bandpass filtered cc's in Fig 1c exhibit a correlation between the seed and previously aliased voxels, which are not present in the fully sampled bandpass filtered cc's, this implies that the correlations artificially induced by the SENSE and GRAPPA models reside within the frequency band commonly associated with that used in fcMRI studies. If unaccounted for, these artificial correlations result in a Type I error, where the voxels are mistakenly found to be functionally connected

REFERENCES

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