Signal Processing Spreads a Voxel's Temporal Frequency Task-Activated Peak and Induces Spatial Correlations in Dual-Task Complex-Valued fMRI

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Background & Purpose: To attenuate noise from image acquisition artifacts and unwanted physiological sources, inherent within the acquired signal, processing operations are applied before the statistical analysis of the data. It is well documented that processing operations modify a voxel's temporal spectrum and induces correlation.[1,2] In this study, spatial correlations are described as a linear combination of second order voxel temporal frequencies using both the magnitude and phase components of the data.[3] The utility of this representation is established with a simulation of dual-task fMRI data. Given a dual-task experimental design with different task periods, two distinct task-activated peaks are expected. Signal processing will alter the activated voxel's temporal frequency spectrums, by spreading voxel task activated peaks temporally and spatially into neighboring frequencies and voxels. If the frequency of the tasks falls within a close range, correlation will be induced between voxels activated by different tasks, as a result of increased overlapping frequency content. Without knowledge of the expected task-activated regions, it is difficult to resolve the task to the associated region after processing. This study contributes to the development of models to account for the impact of signal processing, with respect to the task-activated frequency, while preserving the signal of interest.

Methods: A Monte Carlo simulation is performed with 100 trials of a 96×96 Shepp-Logan phantom scaled to 100 in MATLAB with 720 repetitions and a TR = 1 s. The simulation is generated with a signal-to-noise-ratio (SNR) = 50 and contrast-to-noise-ratio (CNR) = 0.05, by adding normally distributed random noise with a mean = 0 and a standard deviation = 2 to the real and imaginary portions of the time-series, and an experimental block design with an amplitude of 1 is added, to four voxels of interest (VOIs), v_a, v_b, v_c, and v_d. The data is spatially smoothed with a FWHM = 3 voxels, band-pass filtered to analyze temporal frequencies in the range of 0.009-0.1 Hz. Note, the frequency range includes the simulated task-activated frequency peaks. To simulate a dual task experiment, and demonstrate three scenarios are considered. In each scenario, v_a is associated with task 1_a performed for fifteen 24-second periods, *Scenario 1:* v_a vs. v_b; v_b is adjacent to v_a associated with task 2_b performed for eight 45-second periods, *Scenario 2:* v_a vs. v_c; v_c is not within close proximity to v_a associated with task 2_c performed for twelve 30-second periods, *Scenario 3:* v_a vs. v_d; v_d is not within close proximity to v_a associated with task 2_d performed for sixteen 22-second periods. The correlations between voxels are computed with the complex-valued (CV) temporal frequencies, and compared to magnitude only (MO).[3]

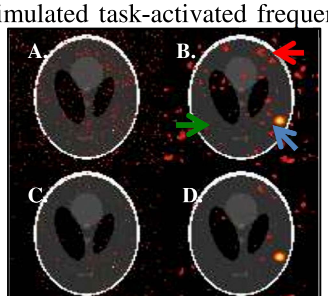

Figure 1: v_a correlation maps: **A.** MO before and **B.** MO after **C.** CV before and **D.** CV after

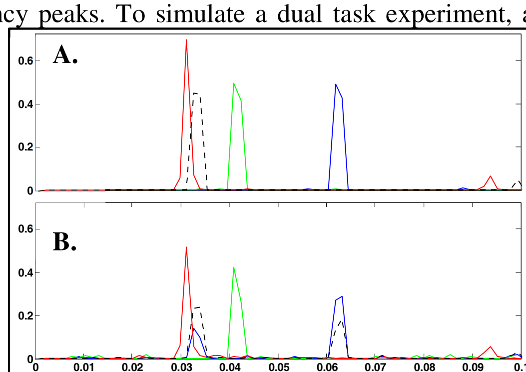

Figure 2: Correlation coefficient contributions at each temporal frequency for v_a (black), v_b (blue), v_b (green), and v_b (red). **A.** before and **B.** after spatial smoothing.

Table 1.	Corr(v_a ,v_b)	Corr(v_a ,v_c)	Corr(v_a ,v_d)
Before	0.0101	-0.0126	0.0217
After	0.8981	0.0766	0.1920

Results & Discussion: Fig. 1 is the before and after processing correlation maps for v_a showing magnitude MO and CV, and the values shown in Fig. 2 are the correlation contributions of the frequency point for each voxel. Note, the arrow color corresponds to voxel location defined in Fig. 2, and the sum of the correlation contributions for each voxel's spectrum sums to 1. In scenario 1, v_a (black) and v_b (blue), demonstrates the impact of spatial smoothing on localized spatial correlation. Before smoothing v_a and v_b share no overlapping frequency content, the smoothing spreads the frequencies of the neighboring voxels into each other's spectrum. Thus, it is difficult to resolve the task with the associated specific region in a dual task-experiment. In scenario 2, v_a (black) and v_c (green), share no initial correlation, and are not within close proximity. Thus, no correlation is induced from the spatial smoothing, and the voxels have distinct activation peaks observed in Fig. 2. In scenario 3, v_a (black) and v_c (red) demonstrate the risk of a dual task-experiment with the tasks having periods that correspond to neighboring activation peaks in the temporal spectrum. These two voxels are not within close proximity to each other, the induced correlation between the two voxels is a result of the temporal frequency content spread to near by frequencies.

Conclusion: The closer the period of the two tasks, the higher the risk of false activation detection will be observed, after processing. The dual-task simulation substantiates the hypothesis that overlapping temporal frequency content leads to induced spatial correlations, which may have no task-based relationship. This study contributes to the development of regression methods to remove signal processing induced correlations, while retaining the signal of interest, to improve the accuracy and reliability of the results, with a potential application to multiband studies and data acquired at high field strengths.

References: **1.**Friston et al., NeuroImage 2000. **2.**Nencka et al., J. Neurosci. Meth. 2009. **3.**Cordes et al., J. Am. NeuroRadiology 2000.

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SYNOPSIS

In a dual-task fMRI experiment, if two tasks are performed at different periods, two distinct task-activated peaks are expected. Signal processing will alter the activated voxel's temporal frequency spectrums, by spreading voxel task activated peaks temporally and spatially into neighboring frequencies and voxels. If both task-activated peaks fall within a close range, correlation will be induced between voxels activated by different tasks, as a result of increased overlapping frequency content from processing. The goal of this study is to describe how signal processing of dual-task complex-valued (CV) fMRI data impacts spatial correlations with respect to the task-frequency.

METHODS

DATA ACQUISITION & PROCESSING: A subject performed a finger tapping task for 15-20s periods and a visual flashing (8Hz) checkerboard task for 12-25s periods, (TR/TE=1000/36ms, BW=250kHz, 4mm oblique slices (oriented to observe both motor and visual tasks), matrix=96×96, slices=12, TRs=600) on a 3.0T GE MR750 scanner. The k-space signal was Nyquist ghost and dynamic B_0-field corrected,[4] IFT reconstructed, and high-pass(<0.009 Hz)/low-pass(>0.08 Hz) ideal band filtered. To demonstrate the impact of smoothing, both CV and MO data is processed separately with a spatial smoothing operator with a Gaussian kernel of FWHM= 2 and 3 voxels.

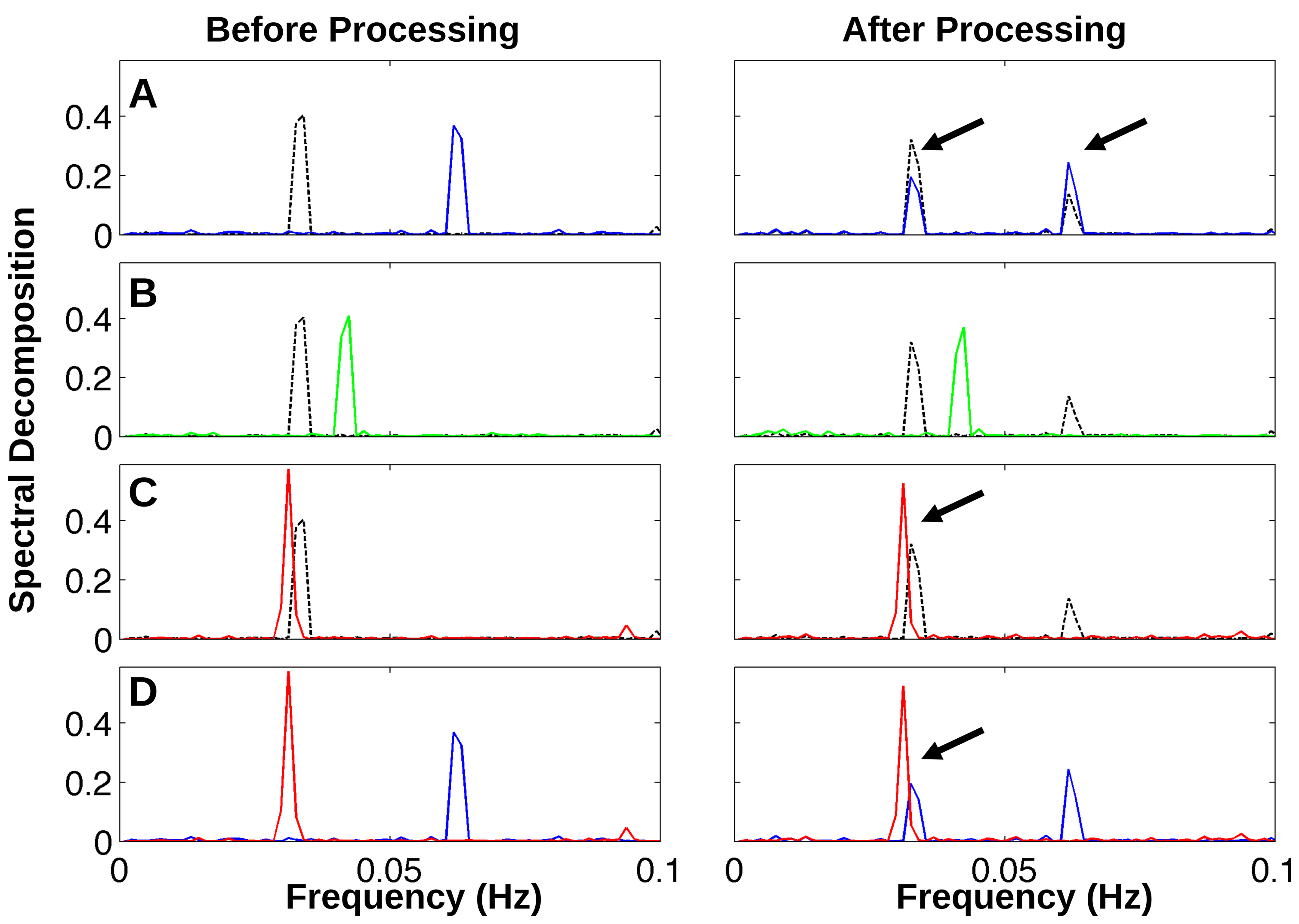
DUAL-TASK EXPERIMENTAL DESIGN RATIONALE: Consider a Matlab CV simulation analyzing the spectral decomposition of 4 voxels (v_a, v_b, v_c, and v_d), each associated with a task performed at a different period. The temporal frequency spectrums are observed before and after spatial and temporal smoothing with a Gaussian kernel of FWHM = 3 voxels/time points. Four scenarios are analyzed in Fig. 1, the arrows indicate increased overlapping frequency content between voxels, and thus an induced correlation.

Scenario 1: v_a vs. v_b; v_b is spatially adjacent to v_a

Scenario 2: v_a vs. v_c; v_c is not within proximity to v_a

Scenario 3: v_a vs. v_d; v_d has a task period close to v_a

Scenario 4: v_b vs. v_d



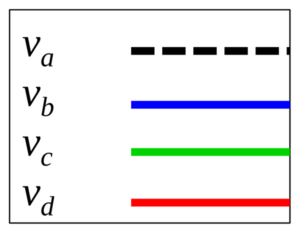


Fig. 1 Spectral decomposition before and after spatial and temporal smoothing with arrows indicating new regions of overlapping frequency content for
(A) *Scenario 1*
(B) *Scenario 2*
(C) *Scenario 3*
(D) *Scenario 4*

Most notably, in Fig. 1D v_b and v_d now share overlapping frequency content, indicating a functional relationship, despite distant spatial locations and a substantial disparity between task peaks.

RESULTS AND DISCUSSION

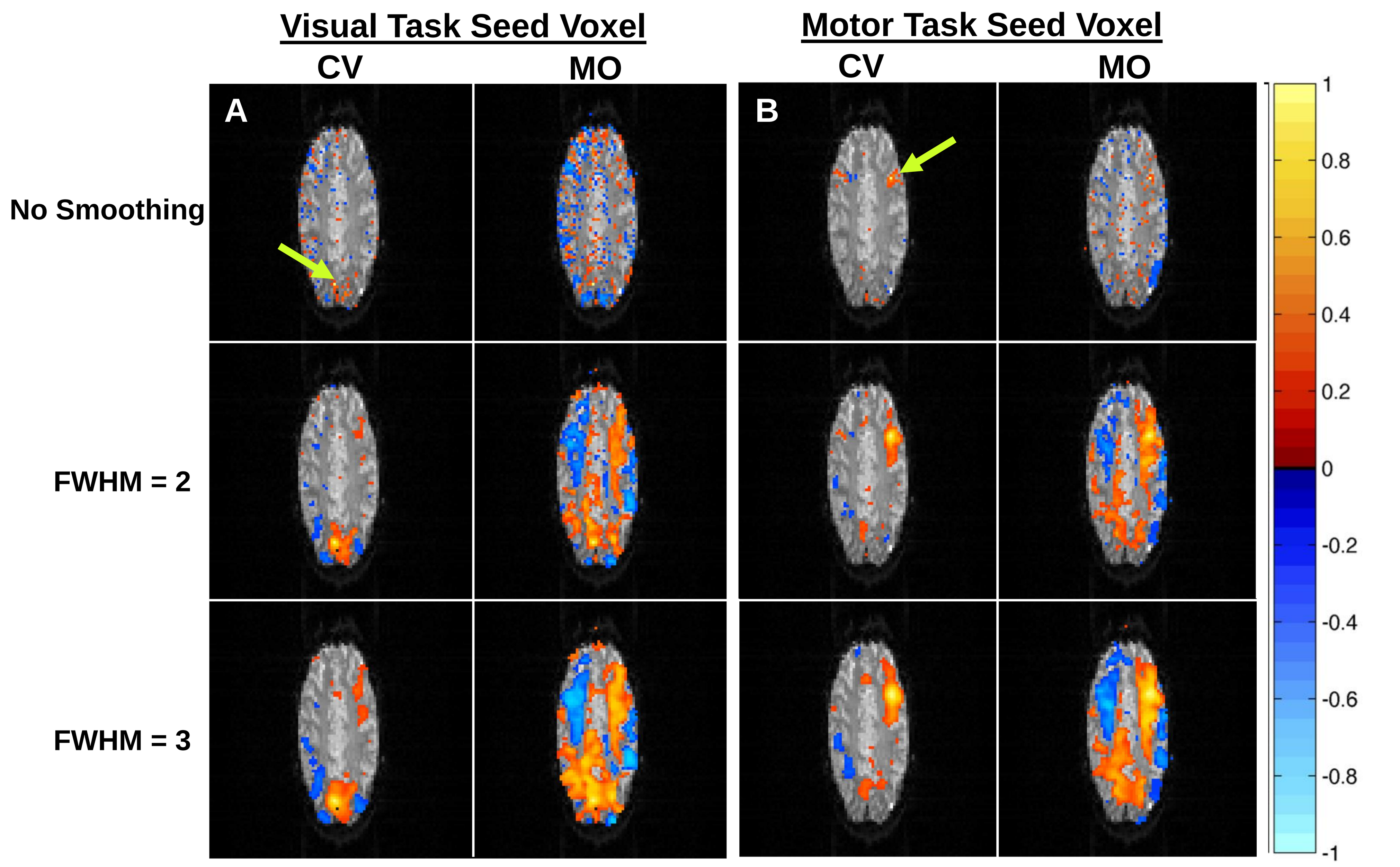


Fig. 2 The CV and magnitude-only (MO) spatial correlation maps of two seed voxels (location indicated with the green arrows), one associated with the **(A)** visual task and the other with **(B)** motor task. Note, the figures are masked and have a threshold of 0.26.

- As seen in Fig. 1, spatial and temporal smoothing modifies a voxel's temporal frequency spectrum, such that the temporal task-activated frequency peak is spread, potentially leading to false conclusions.
- As seen in Fig. 2, two seed voxels are chosen based on their respective functional activation locations.[5] Spatial correlation is computed with the temporal Fourier frequencies such that both the magnitude and phase can be incorporated into the calculation, and increased overlapping frequency between voxels content yields higher correlation between the voxels.
- Fig. 2 validates the statistical power of implementing CV models in fMRI studies, before applying the smoothing operator, the seed voxels are correlated with the voxels in their cortex in the CV maps. In the MO maps, the spatial correlation in the motor and visual cortices is difficult to distinguish before smoothing is applied. As expected, increasing the FWHM increases the correlated region size in CV and MO data. While the simulation in Fig. 1 suggests the spatial smoothing contributes to the induced spatial correlation between the two cortices in Fig. 2, subsequent data sets must be studied to further investigate this hypothesis.

CONCLUSION

This study contributes to the development of complex-valued models to account for the impact of signal processing, with respect to the task-activated frequency. Specifically, it is important to preserve the signal of interest, in order to avoid inducing correlation from overlapping temporal frequency content between voxels with no task-based relationship.

REFERENCES

1.Friston et al., NeuroImage 2000. **2.**Nencka et al., J. Neurosci. Meth. 2009. **3.** Cordes et al., J. Am. NeuroRadiology 2000. **4.** Hahn et al., HBM 2011. **5.** Rowe NeuroImage. 2005.