Matched Filter EPI Increases BOLD-Sensitivity in Human Functional MRI

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INTRODUCTION
Post processing of MR images is omnipresent: for fMRI in particular, smoothing of the raw images is frequently applied to gain SNR on the spatial scale of the BOLD response (‘matched filter’). This shaping of the point spread function (PSF) acts complementary to sampling itself, where the choice of a k-space trajectory imposes an intrinsic filter onto the data. We combine both approaches to pursue SNR optimization through the choice of an optimal acquisition strategy, incorporating the prior knowledge about the target smoothing kernel. Specifically, the implications for temporal SNR and fMRI t-maps in the case of Gaussian weighting are considered for a 2D gradient-velocity modulated EPI.

METHODS
It turns out that the SNR in the final (post-processed) image is optimal, when k-space is acquired with non-uniform density. More precisely, the optimal acquisition k-space weighting \( d_{\text{eq}} \) (in the presence of white thermal noise and obeying the Nyquist criterion) is the Fourier transform of the desired (or target) PSF in the image domain, i.e. the smoothing kernel \( d_{\text{target}}(k) = FT\{d_{\text{target}}(r)\} \).

This derives from the fact that k-space density-weighting during acquisition is a type of averaging that scales the noise variance linearly, whereas smoothing during post-processing acts as a scaling factor to the noise and induces a quadratic scaling of the variance. Thus, the noise variance \( \sigma^2 \) in k-space after performing (image-domain) smoothing is given by \( \sigma^2(k) \propto \frac{d_{\text{eq}}(k)}{d_{\text{target}}(k)} \) (1) from which \( d_{\text{eq}}(k) = d_{\text{target}}(k) \) follows, when minimizing under the constraint of constant acquisition time [1]. We approximated this ideal Gaussian ‘matched filter’ using a 2D Gaussian velocity-weighted single-shot EPI (Fig. 1). To achieve maximum SNR, we performed a uniform EPI of equal duration.

Simulations incorporating system gradient constraints were performed to estimate the SNR gain. Measurements were made in a phantom (CuSO₄-doped water, \( n = 100 \) densities, TR 1 s, 2 interleaves) and in resting-state in-vivo time series (\( n = 40 \)) on a Philips Achieva 3T system (Philips Healthcare, Best, NL) with an 8-channel receive head coil and transmit body coil.

RESULTS
Temporal SNR (tSNRthermal) was assessed via separate noise scans, which were added to a vehicle signal scan for reconstruction: \( tSNR_{\text{thermal}} = \frac{\text{mean(smoothed signal scans)}}{\text{sd(smoothed noise instances)}} \). To investigate the additional influence of physiological noise, we conducted an fMRI experiment with block-wise stimulation of either the upper left and lower right visual hemi-fields, or vice versa (flickering colored wedges, \( 17 \) s block-length, \( 3 \) s fixation, \( 10 \) min duration). A general linear model analysis (GLM) was performed in SPM8 (Functional Imaging Laboratory, London) to retrieve peak t-values and cluster sizes of the generated contrast maps after multiple-comparison correction (FWE \( p = 0.05 \)).

<table>
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<tr>
<th>TABLE 1: MEAN VOXEL SNR RATIO GAUSS/EPI</th>
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Given the resolution and smoothing kernel, eq. (1) can be solved analytically in 2D for a perfect Gaussian vs. an ideal uniform density. We found comparable SNR increases in simulations (where EPIs give unfavorable higher-frequency weighting due to their “u-turns”) as well as both phantom and in-vivo resting-state measurements (Tab. 1, Fig. 2). Moreover, the sensitivity of statistical analyses in the fMRI paradigm increased for the density-weighted trajectory, observable by larger cluster sizes (red: 3D vs. 2 voxels, blue: 27 vs. 4) and peak t-values (red: \( t = 39.77/35.64 \), blue: 37.30/32.39) (Fig. 3).

CONCLUSION
It was shown that by using a suitable trajectory the temporal thermal SNR in post-processed images can be increased by 60-80%. This comes at no cost in terms of measurement time or resolution in the final (smoothed) images. Thereby, also the sensitivity of the BOLD-fMRI acquisition was increased as demonstrated in a visual paradigm enhancing the detection and robustness of smaller clusters – which confirms the significance of thermal contributions to the noise sources at 3T.

REFERENCES