2D Parallel Imaging with RASER for True Whole Brain fMRI at 7 T

Ute Goerke[1], Craig Moodie[2], Krista Wisner[2], and Angus MacDonald III[2]

[1]CMRR, University of Minnesota, Minneapolis, Minnesota, United States, [2]Psychology, University of Minnesota, Minneapolis, Minnesota, United States

Introduction:
Previously, it was demonstrated that RASER provides activation maps of superior quality in the orbitofrontal cortex (OFC) in humans compared to conventional echo-planar imaging (EPI) which is affected by magnetic field variations near-air tissue interfaces [1]. RASER, however, is limited in its capability to achieve whole brain coverage with acceptable spatiotemporal resolution in fMRI studies. In order to overcome this limitation, a novel two dimensional parallel imaging strategy for RASER is implemented in the presented work. We demonstrate that true whole-brain coverage in fMRI at 7 T is not only achieved by simply extending the field-of-view (FOV), but also that RASER's unique property of detecting activation in brain regions close to air cavities is retained.

Method:
RASER is based on so-called spatiotemporal (st) encoding using a frequency-swept excitation pulse to sequentially excite transverse magnetization M_t in the direction of the gradient G_{st} (Fig. 1). M_t is refocused by two 180°-pulses as an echo train: the first echo originates from a plane on one side and the last from the other side of the FOV. The echoes come from adjacent planes of thickness 1 voxel = FOV/number of echoes and orthogonal to G_{st}. The echoes are frequency-encoded using alternating readout gradient lobes G_f similar to EPI. Fourier-transformation along the readout direction G_f provides a 2D image. In order to encode the third spatial dimension a phase-encoding gradient (gray-shaded lobe of G_s) is incremented in subsequent scans. Fourier-transformation of this coordinate generates a 3D image.

For the fMRI scan the acquisition scheme was accelerated in two spatial dimensions: the st-encoded and the phase-encoded dimension. Since st-encoding is similar to properties of slice-selection, aliasing cannot be generated by simply reducing the FOV. To achieve the desired overlap of signal from different regions several 'slices' have to be excited simultaneously. This is achieved by employing a multi-band frequency-swept excitation pulse, which is generated by superimposing CHIRP-pulses with different spatial offsets generated by linear phase-modulation [2]. The third dimension is accelerated by choosing the phase-encoded FOV to be smaller than the slab thickness determined by G_s.

GRAPPA [3] is performed first on the accelerated st-encoded dimension and then on the phase-encoded third spatial dimension using a full-FOV scan acquired prior to the fMRI scan. The constant gradient G_{st} during the echo train modulate the signal phase proportional to time during data acquisition. Therefore, all echoes have to be phase-corrected before Fourier-transformation.

Experimental:
Experiments were performed on a 7 T Siemens scanner console using a volume head coil with 32 receive channels. Eight volunteers participated in the first and four in the second fMRI study after written consent. Imaging parameters are provided in the figure captions. In all studies, B_1-shimming was applied to minimize flip angle variations across the brain [4].

In the fMRI studies, a common working memory paradigm (n-back) that was modulated by the potential for gains or losses was employed. Participants were instructed to press the "target" button whenever the current word matched the word presented n number of words beforehand. During neutral feedback blocks, participants saw a constant value of winnings on the screen, irrespective as to whether they made an error. During gain blocks, the participants would win 25 cents for correct answers and would not lose anything for incorrect answers. For the lose condition the participant would lose 25 cents if they answered incorrectly and they would not receive any money for correct answers. Participants were scanned for three 30 s long blocks for each of six conditions.

Results and discussion:
Fig. 2 shows an example of the brain coverage which can be achieved with RASER with 2D acceleration. Sufficient signal without blurring and distortion is obtained in the OFC (see arrows in Fig. 2). The contrast in the RASER images is suppressed due to the way GRAPPA reconstruction is performed.

Fig. 3 shows activation in the OFC induced by the modified working memory task. These results which were obtained with accelerated RASER demonstrate the predicted main effects in regions associated with working memory load (top panel), reward (middle panel) and punishment (bottom panel). In summary, accelerated RASER can provide true whole brain coverage for fMRI at ultra-high magnetic field strength.

References:
[1] Goerke U et al., NeuroImage **54**: 350 (2011); [2] Nguyen T et al., Proc. Intl. Soc. Mag. Reson. Med. **17**: 2738 (2009); [3] Griswold MA et al., MRM **47**: 1202 (2002); [4] van de Moortele P-F et al., MRM **54**: 1503 (2005); [5] Ugurbil K et al., JMR **80**: 448 (1988).
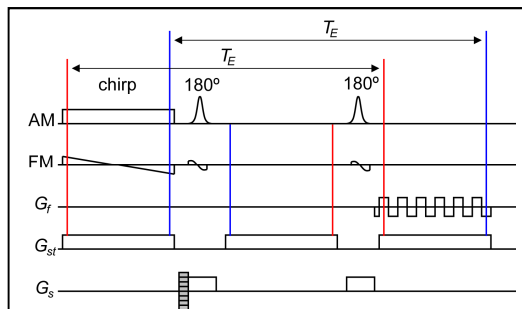
Figure 1: RASER pulse sequence. Red indicates transverse magnetization which is excited and refocused early, blue marks magnetization excited and refocused late while maintaining a constant T_E for all echoes.
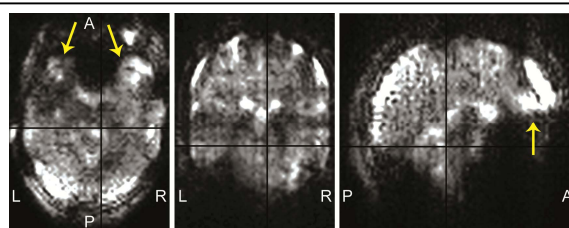

Figure 2: Transverse, coronal and sagittal cross-sections of a single volume from a fully reconstructed RASER time series (second fMRI study) acquired with quad-band excitation with an time-bandwidth product of $R = 60$, an acceleration of six in the phase-encoded dimension G_s, reconstructed matrix size: 88x88x60, an isotropic resolution: 2.5 mm, a volume-to-volume T_R: 7.0 s, T_E: 66 ms. The 180°-pulses are non-slice selective NOM-pulses [5]. The black lines mark the location of the displayed slices.
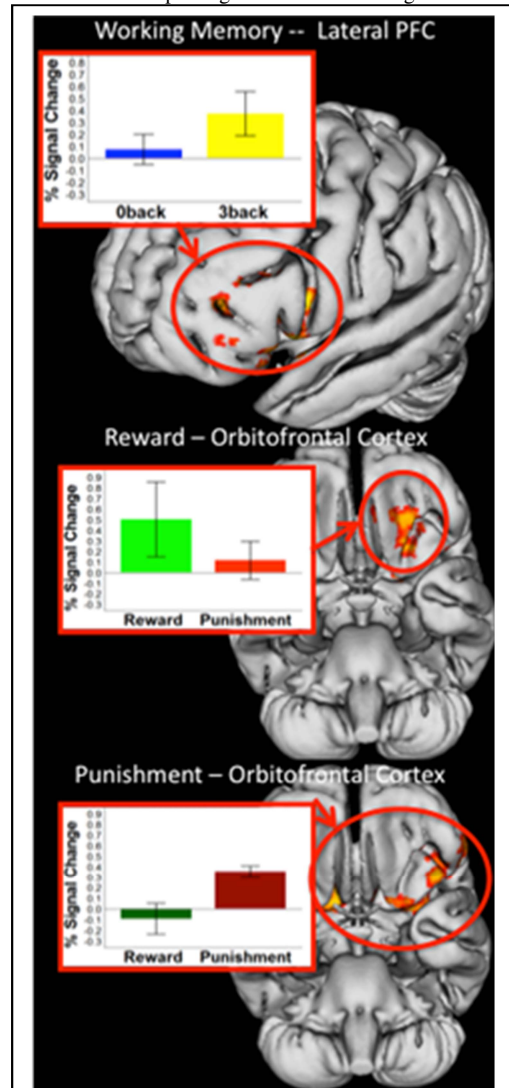

Figure 3: Activation patterns in lateral PFC (BA 46/45) and orbitofrontal cortex (BA 11/47) in a working memory task (n-back) with reward and punishment. Main effects from five participants (first fMRI study) thresholded using a prefrontal cortex mask with small-volume correction ($p<.05$). RASER time series were acquired with quad-band excitation (time-bandwidth product $R = 100$), an acceleration factor of four in the phase-encoded dimension G_s, final image matrix: 96x96x64, isotropic resolution: 2.5 mm, volume-to-volume T_R: 6.4 s, T_E: 70 ms. The refocusing pulses were slice-selective adiabatic hyperbolic secant pulses (HS1, $R = 10$).