THE EFFECT OF FLIP ANGLE ON BOLD FMRI SENSITIVITY

J. Gonzalez-Castillo¹, V. Roopchansignh², P.A. Bandettini¹,², J. Bodurka³

¹ Section on Functional Imaging Methods, LBC, NIMH, NIH, Bethesda, MD
² Functional MRI Facility, NIMH, NIH, Bethesda, MD
³ Laureate Institute for Brain Research, Tulsa, OK
WHY SHOULD WE CONSIDER LOW FLIP ANGLES ($\theta$)?

- Reduction of RF Power $\Rightarrow$ Lower Heat Deposition
- Limitation of Apparent $T_1$-related Inflow Effects
- Reduction of In-Plane Motion Artifacts
- Lower Levels of Physiological Noise
- Higher Tissue Contrast $\Rightarrow$ Improved Alignment

IF LOW $\theta$ ARE SO GOOD, WHY PEOPLE COMMONLY CHOOSE THE ERNST ANGLE ($\theta_{\text{ERNST}}$)?

- Maximizes Signal Level
- Maximizes Image Signal-to-Noise Ratio (SNR)

But, what about Temporal Signal-to-Noise Ratio (TSNR) or Task-based BOLD Contrast? Are we necessarily also maximizing those?
**SIGNAL IN GRE-EPI DATA**

\[ S = M_o \cdot e^{-TE/T_2^*} \cdot \frac{(1 - e^{-TR/T_1}) \cdot \sin(\theta)}{1 - e^{-TR/T_1} \cdot \cos(\theta)} \]

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**NOISE IN GRE-EPI DATA**

**RAW NOISE \([\sigma_o]\)**

- Thermal Noise from Scanner/Subject
- Drift, Gradient Imperfections, etc.

\[ \sigma_o \not\propto S \]

**PHYSIOLOGICAL NOISE \([\sigma_p]\)**

- Fluctuations in Basal Metabolism
- Fluctuations from Cardiac/Respiratory Functions

\[ \sigma_p = \lambda \cdot S \]

**TOTAL NOISE \([\sigma_{TOTAL}]\)**

\[ \sigma_{TOTAL} = \sqrt{\sigma_o^2 + \sigma_p^2} \]

\[ \sigma_{TOTAL} \propto S \]

Krüger et al. (2001)
MRI DATA QUALITY METRICS AND THEIR RELATIONSHIP

**DATA QUALITY** = \( \frac{\text{SIGNAL LEVEL}}{\text{NOISE LEVEL}} \)

**IF NOISE LEVEL = \( \sigma_o \)**

\[ SNR = \frac{S}{\sigma_o} \]

*NOISE* = spatial standard deviation (SD) of intensity values in ROI outside the brain

**IF NOISE LEVEL = \( \sigma_{\text{TOTAL}} \)**

\[ TSNR = \frac{S}{\sqrt{\sigma_o^2 + \sigma_p^2}} \]

*NOISE* = voxel-wise temporal SD of intensity across steady-state volumes.

**SNR & TSNR SHOW A NON-LINEAR RELATIONSHIP**

\[ TSNR = \frac{S}{\sqrt{\sigma_o^2 + \sigma_p^2}} \]

\[ TSNR = \frac{SNR}{\sqrt{1 + \left(\frac{\sigma_p}{\sigma_o}\right)^2}} \]

**IF THERMAL NOISE DOMINATES**

\[ \frac{\sigma_p}{\sigma_o} \ll 1 \]

TSNR \( \approx \) SNR

**IF PHYSIOLOGICAL NOISE DOMINATES**

\[ \frac{\sigma_p}{\sigma_o} \gg 1 \]

TSNR \( \neq \) SNR
When Physiological Noise Dominates, Flip Angles well below the Ernst Angle produce minimal loss in TSNR.
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EXPRESSIMENTAL MOTIVATION & GOALS

1. TEST THEORETICAL PREDICTIONS ON HOW SNR AND TSNR CHANGE WITH FLIP ANGLE

   - ACQUIRE DATA AT SEVERAL ANGLES
   - COMPUTE SNR & TSNR

   EXPECTED OUTCOME
   REPRODUCE THEORETICAL SNR/TSNR CURVES WITH REAL HUMAN DATA

2. TEST IF BOLD FMRI AT LOW FLIP ANGLES PRODUCES RESULTS COMPARABLE TO BOLD FMRI AT ERNST ANGLE WHEN PHYSIOLOGICAL NOISE DOMINATES

   - HEMODYNAMIC RESPONSE
   - REGRESSION COEFFICIENTS (β)
   - ACTIVATION MAPS

   EXPECTED OUTCOME
   FLIP ANGLE HAS NO SYSTEMATIC EFFECT ON ANY OF THESE METRICS
METHODS: Data Acquisition

- Eight Subject (4 Males + 4 Females)
- Scanner: 3T Signa HDx | Coil: 16-Channel Nova Medical
- Data Collection:
  - Anatomical Scan: MPRAGE
  - Functional Scans: GRE-EPI
    - TE/TR=30/2000ms; FOV=24cm; 32 Slices; In-plane: 64x64; Thickness=4.0mm
    - $\theta = 9^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ, 105^\circ, 120^\circ$ ($9^\circ$ & $120^\circ$ only in 7 subjects)
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**METHODS: Data Processing**

### DATA PRE-PROCESSING
- Intra-run Motion Correction
- Spatial Co-registration
- Discard Initial 5 Volumes
- Data Detrending
- Spatial Smoothing (FWHM = 6mm)
- Intensity Scaling (divide by the mean)

### STATISTICAL ANALYSIS
- AFNI 3dREML
- Contrast: Task vs. Rest
- Threshold: $p_{FDR} < 0.05$

### ROI ANALYSIS
- Tissue ROIs (Method by Bodurka et al. 2007):
  - Grey Matter, White Matter, CSF.
- Task Related ROIs (From AFNI Atlases):
  - Right & Left Visual Cortex, Left Primary Motor Cortex
RESULTS: SNR & TSNR vs. FLIP ANGLE

GREY MATTER

WHITE MATTER

CSF

λ | .0092 ± .0023
λ | .0040 ± .0011
λ | .0158 ± .0072
RESULTS: ESTIMATED HEMODYNAMIC RESPONSES

- **RIGHT VISUAL CORTEX**
- **LEFT VISUAL CORTEX**
- **LEFT PRIMARY MOTOR CORTEX**

(2) TEST IF BOLD FMRI AT LOW FLIP ANGLES PRODUCES RESULTS COMPARABLE TO BOLD FMRI AT ERNST ANGLE
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## RESULTS: STATISTICAL ACTIVATION MAPS

<table>
<thead>
<tr>
<th>SUBJET 1</th>
<th>SUJBET 3</th>
<th>SUJBET 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>L</td>
<td>R</td>
</tr>
</tbody>
</table>

### REPRODUCIBILITY ACROSS ANGLES

<table>
<thead>
<tr>
<th>ROI Type</th>
<th>Visual ROI</th>
<th>Motor ROI</th>
<th>Whole Brain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{overlap}}$</td>
<td>0.91 ± 0.04</td>
<td>0.76 ± 0.09</td>
<td>0.65 ± 0.06</td>
</tr>
</tbody>
</table>

### PREV. REPORTED INTRA-SESSION TEST-RETEST

<table>
<thead>
<tr>
<th>Task Type</th>
<th>Flashing Checker</th>
<th>Finger Tapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>0.56 – 0.66*</td>
<td>0.41 – 0.50**</td>
</tr>
</tbody>
</table>

*Miki et al. (2001); **Gountouna et al. (2010), Tegeler et al. (1999)
RESULTS: REGRESSION COEFFICIENTS (β)

- SUBJECT 01: \( \beta_{15} = 1.08 \times \beta_{75} - 0.37 \)
- SUBJECT 06: \( \beta_{45} = 0.96 \times \beta_{75} + 0.19 \)
- SUBJECT 03: \( \beta_{120} = 0.84 \times \beta_{75} + 0.08 \)

Bar graph showing the slope (S) and constant (C) across different flip angles.

(2) TEST IF BOLD FMRI AT LOW FLIP ANGLES PRODUCES RESULTS COMPARABLE TO BOLD FMRI AT ERNST ANGLE.
CONCLUSIONS

1. Theoretical predictions on how SNR and TSNR change with flip angle confirmed experimentally.

2. BOLD FMRI at low flip angles produces results comparable to BOLD FMRI at Ernst angle.

What angle do you suggest to use? Should it be 10°? 30°?

What experimental factors affect this suggested angle?
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**SUGGESTED FLIP ANGLE (I)**

Imaging at angles well below the Ernst angle is possible only when physiological noise is the dominant noise source.

Two experimental factors define whether or not we are dominated by physiological noise.

**Physiological Noise Level ($\lambda$)**

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>SNR</th>
<th>TSNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0$</td>
<td>780</td>
<td>400</td>
</tr>
<tr>
<td>$1e^{-3}$</td>
<td>700</td>
<td>500</td>
</tr>
<tr>
<td>$2e^{-3}$</td>
<td>600</td>
<td>400</td>
</tr>
<tr>
<td>$3e^{-3}$</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>$4e^{-3}$</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>$5e^{-3}$</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>$6e^{-3}$</td>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>$7e^{-3}$</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>$8e^{-3}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$9e^{-3}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$1e^{-2}$</td>
<td>0</td>
<td>0</td>
</tr>
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**Available Image SNR**

<table>
<thead>
<tr>
<th>SNR</th>
<th>TSNR</th>
</tr>
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<tbody>
<tr>
<td>$100$</td>
<td>700</td>
</tr>
<tr>
<td>$200$</td>
<td>700</td>
</tr>
<tr>
<td>$400$</td>
<td>700</td>
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<tr>
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## SUGGESTED FLIP ANGLE (II)

SUGGESTED FLIP ANGLE = FLIP ANGLE FOR WHICH NO NOISE SOURCE DOMINATES

\[ \sigma_p / \sigma_o = 1 \]

IF \((TR >> T_1)\)

\[ \theta_S = \sin^{-1} \left( \frac{1}{\lambda \cdot SNR_o} \right) \]

<table>
<thead>
<tr>
<th>T R</th>
<th>(\theta_{ERNST})</th>
<th>RESOLUTION [mm]</th>
<th>(\theta_{SUGGESTED BIRDCAGE})</th>
<th>(\theta_{SUGGESTED 8CH ARRAY})</th>
<th>(\theta_{SUGGESTED 16CH ARRAY})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s</td>
<td>62°</td>
<td>3.8x3.8x4</td>
<td>(\theta_{ERNST} \approx 62°)</td>
<td>&gt;25°</td>
<td>&gt;10°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.8x1.8x2</td>
<td>(\theta_{ERNST} \approx 62°)</td>
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<td>(\theta_{ERNST} \approx 62°)</td>
</tr>
<tr>
<td>2s</td>
<td>77°</td>
<td>3.8x3.8x4</td>
<td>(\theta_{ERNST} \approx 77°)</td>
<td>&gt;25°</td>
<td>&gt;10°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.8x1.8x2</td>
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<td>(\theta_{ERNST} \approx 77°)</td>
</tr>
<tr>
<td>3s</td>
<td>83°</td>
<td>3.8x3.8x4</td>
<td>(\theta_{ERNST} \approx 83°)</td>
<td>&gt;25°</td>
<td>&gt;10°</td>
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IF INTERESTED IN MORE DETAILS, PLEASE CHECK OUR PAPER:

**Physiological noise effects on the flip angle selection in BOLD fMRI**

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\textsuperscript{a} Section on Functional Imaging Methods, Laboratory of Brain and Cognition, National Institute of Mental Health, National Institutes of Health, 10 Center Dr, Bethesda, MD 20892, USA

\textsuperscript{b} Functional MRI Facility, National Institute of Mental Health, National Institutes of Health, 10 Center Dr, Bethesda, MD 20892, USA

\textsuperscript{c} Laureate Institute for Brain Research, 5555 South Yale Avenue, Tulsa, OK 74136, USA

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