BMDE610: Functional Neuroimaging Fusion

Assignment Report

Minimum-Norm Source Localization in Brainstorm

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1. Methods

All experiments used the same averaged background file data_average_120321_0624.mat (which corre sponds to Avg: Background_1_10 in Brainstorm).

The important correction relative to the earlier implementation was in the source parameterization. The head model stores an unconstrained gain matrix with three Cartesian orientations for each cortical vertex. However, the source space is the `white_6000V` cortical mesh, and the scout vertices index cortical locations rather than arbitrary orientation columns. In the final implementation, the unconstrained gain matrix was projected onto the surface normals (`GridOrient`) so that the inverse operated on one scalar amplitude per cortical vertex. Previously I had used `Scouts.Vertices` direclty as column indices and activated `Jtheo(Scouts.Vertices)`, So we were only turning on one Cartesion block of a free-orientation model, not a cortical source on the scout patch.

1.1. Important note on timing

The code labels the spike center as 150 ms But how I moved forward with the implementation, the waveform at a sample that corresponds to an actual peak is near 6.67 ms in the stored epoch. All peak topographies and source maps shown in the Results section were actually evaluated at 6.67 ms.

2. Results

2.1. Experiment 1: Effect of noise level

Case	SNR	Best alpha	Peak |MEG| (T)	Vertices $\geq$ 50% max	Localization error
`noiseLow`	2	2.78e-12	4.83e-13	29	5.52 mm
`noiseHigh`	6	5.18e-12	1.10e-12	3	5.52 mm

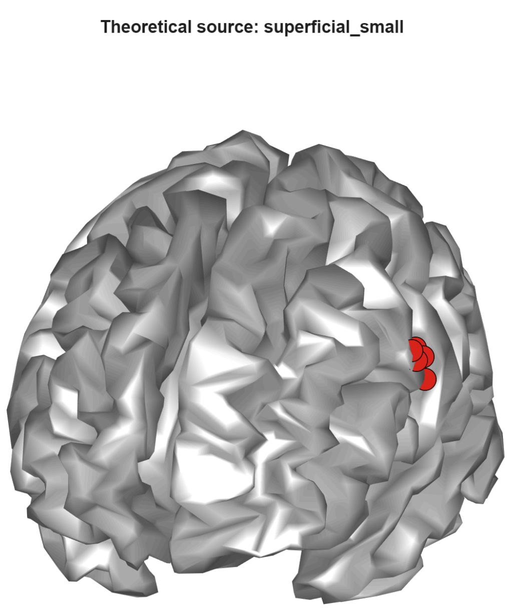

Figure 1: Vertices of theoretical source (red dots) used for the noise experiment. The same superficial scout support (`scout_superficial_small.mat`) was used in both noise conditions.

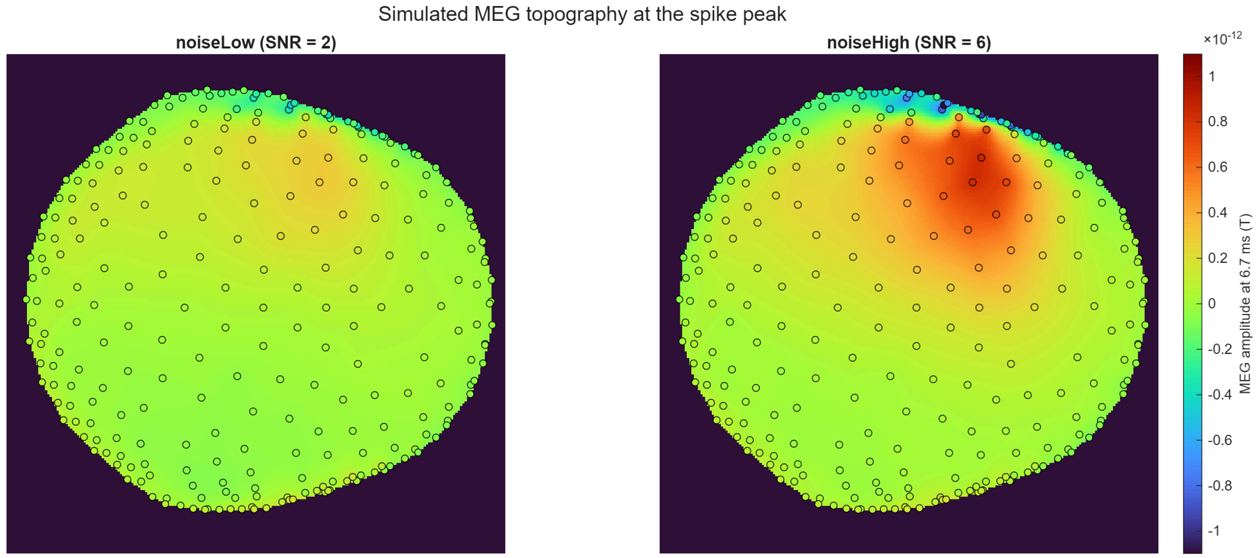

Figure 2: Simulated MEG topography at the spike peak for the two noise conditions. The higher-SNR run produces a substantially larger sensor-level response (1.10 pT versus 483e fT) while having the same overall topography pattern.

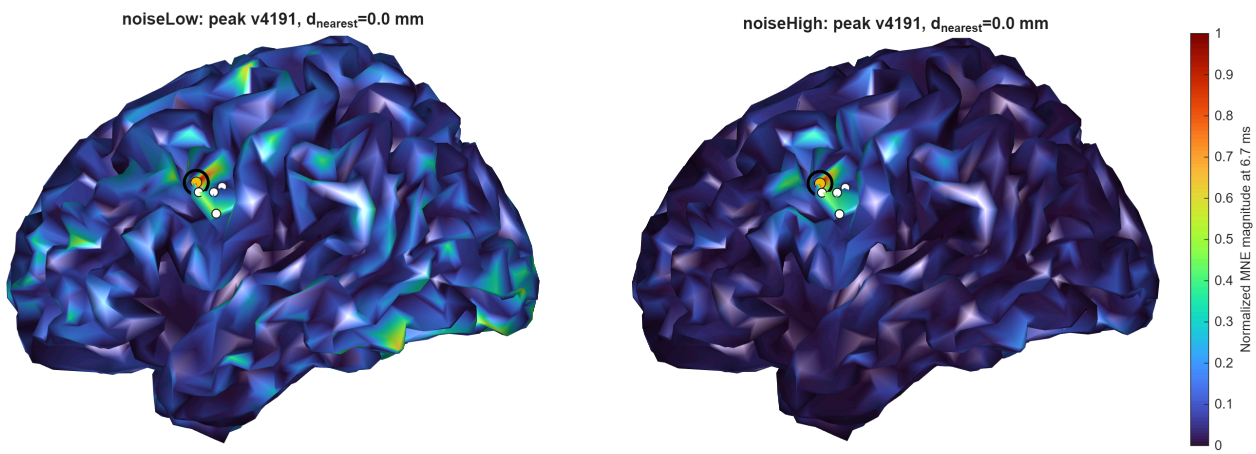

Figure 3: MNE source localization at the spike peak for the two noise conditions. The white dots indicate the theoretical 5-vertex scout and the yellow circled marker indicates the dominant estimated vertex. In both cases the dominant estimated vertex was 4191 which is one of the active theoretical scout vertices.

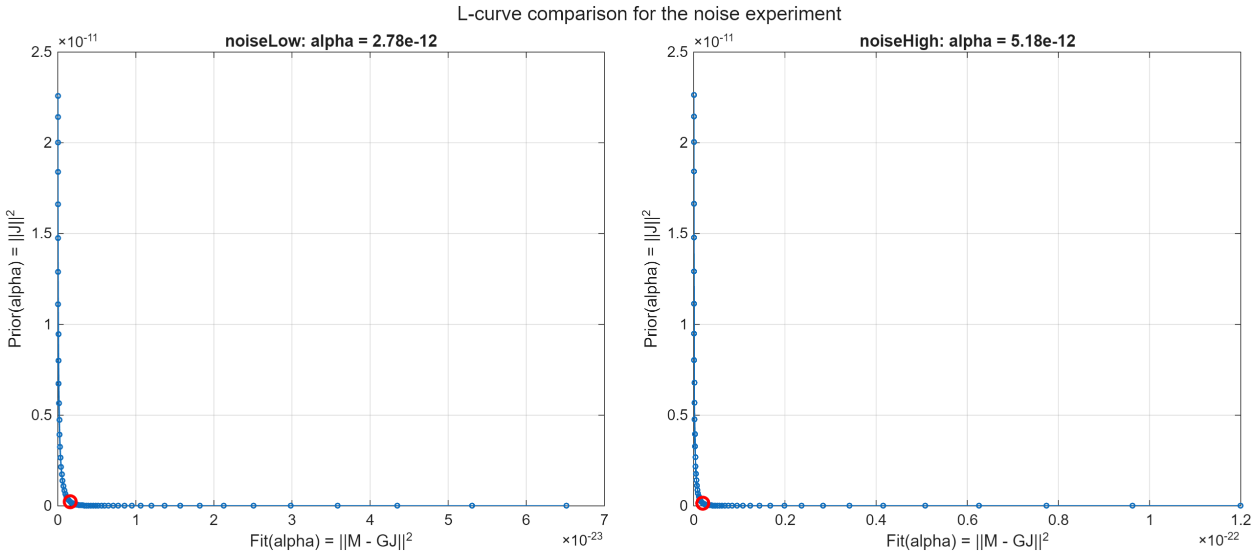

Figure 4: L-curve comparison for the noise experiment. The normalized cost selected $\alpha = 2.78 \cdot 10^{-12}$ for `noiseLow` and $\alpha = 5.18 \cdot 10^{-12}$ for `noiseHigh`.

The corrected source model makes the noise experiment much more interpretable than before. In both runs, the estimated peak falls directly on the theoretical scout support. Increasing the SNR strengthened the sensor response and also made the normalized MNE map more focal. The number of vertices above `50%` of the peak dropped from `29` to `3`, and the dominant source vertex did not change. This is a reasonable behavior for standard MNE, as once the true cortical patch is already correctly identified, higher SNR improves contrast more than it changes the peak position.

2.2. Experiment 2: Effect of source depth

Case	**Distance to head (mm)**	**Best alpha**	**Peak |MEG| (T)**	**Vertices $\geq 50\%$ max**	**Localization error (mm)**
`depthSuper`	`19.30`	`3.79e-12`	`7.91e-13`	`3`	`5.52`
`depthDeep`	`30.02`	`2.78e-12`	`3.63e-13`	`69`	`105.89`

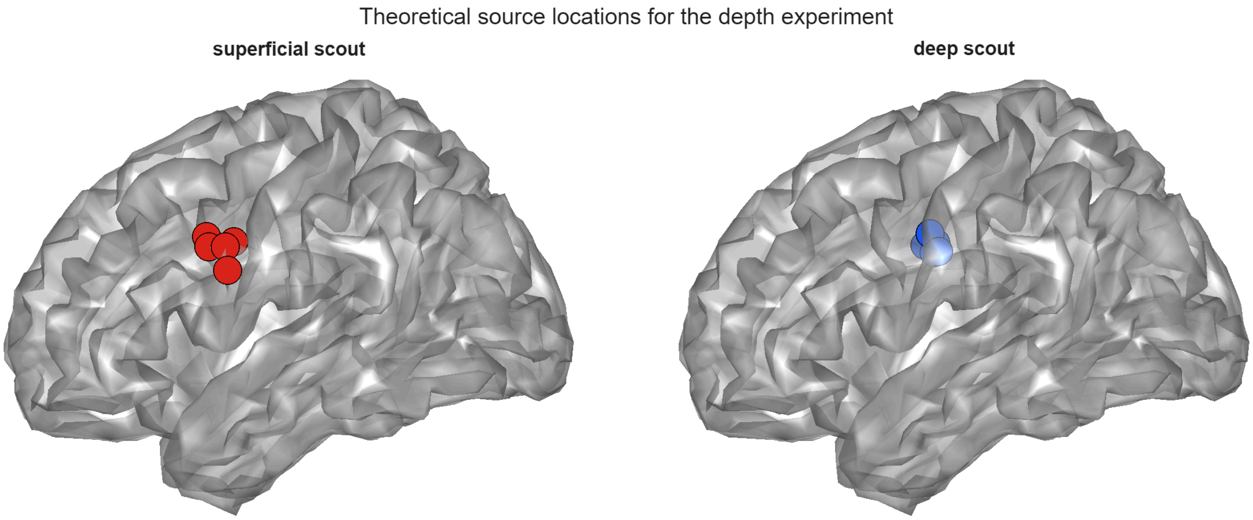

Figure 5: Theoretical cortical source locations used for the depth experiment. The superficial and deep scouts are shown in matched lateral views, with the cortical surface rendered semi-transparently so the deeper placement remains visible.

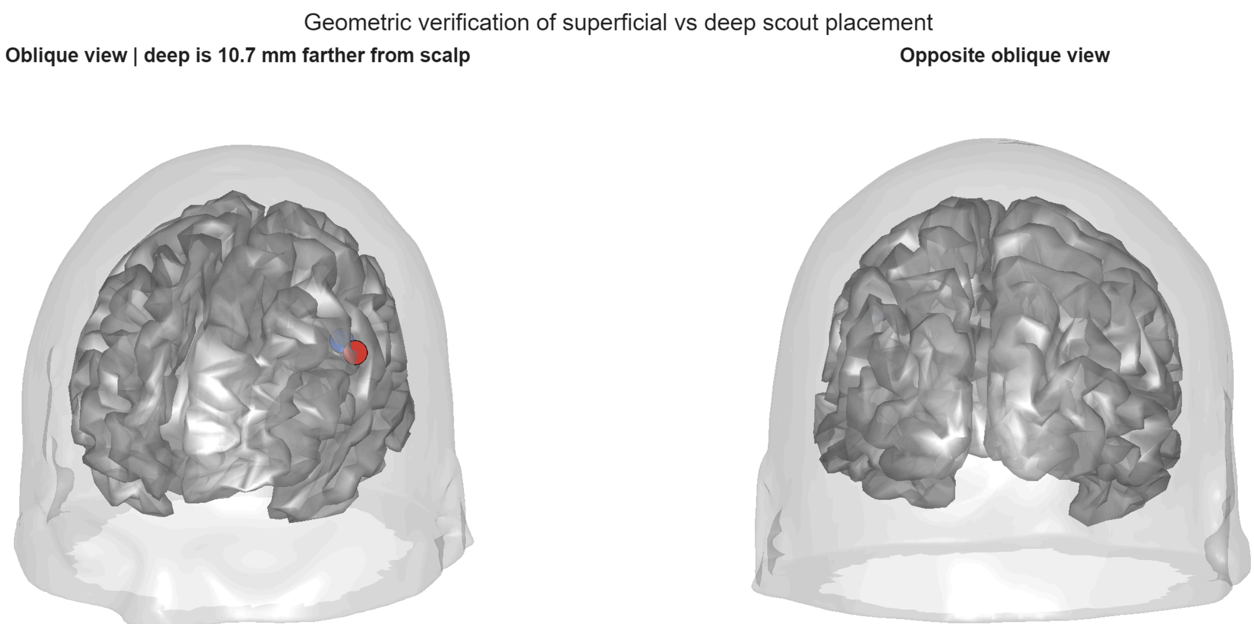

Figure 6: Geometric verification of scout placement relative to the head surface. The deep scout lies `10.71 mm` farther from the scalp than the superficial scout.

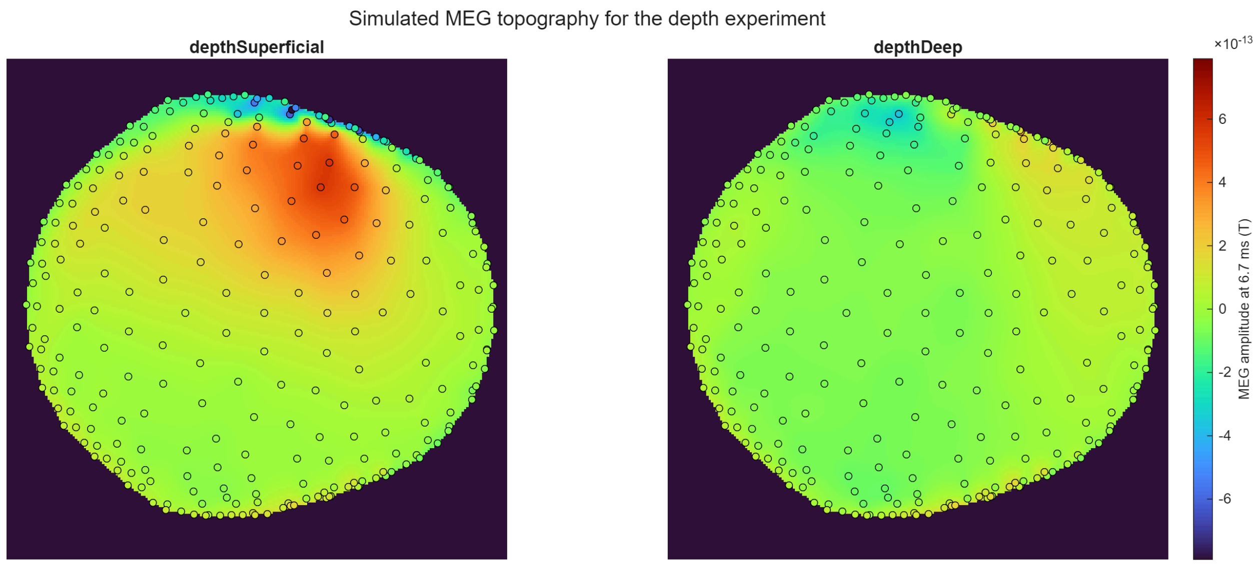

Figure 7: Simulated MEG topography at the spike peak for the depth experiment. The deeper source produces a substantially weaker MEG field (363 fT) than the superficial source (791 fT)

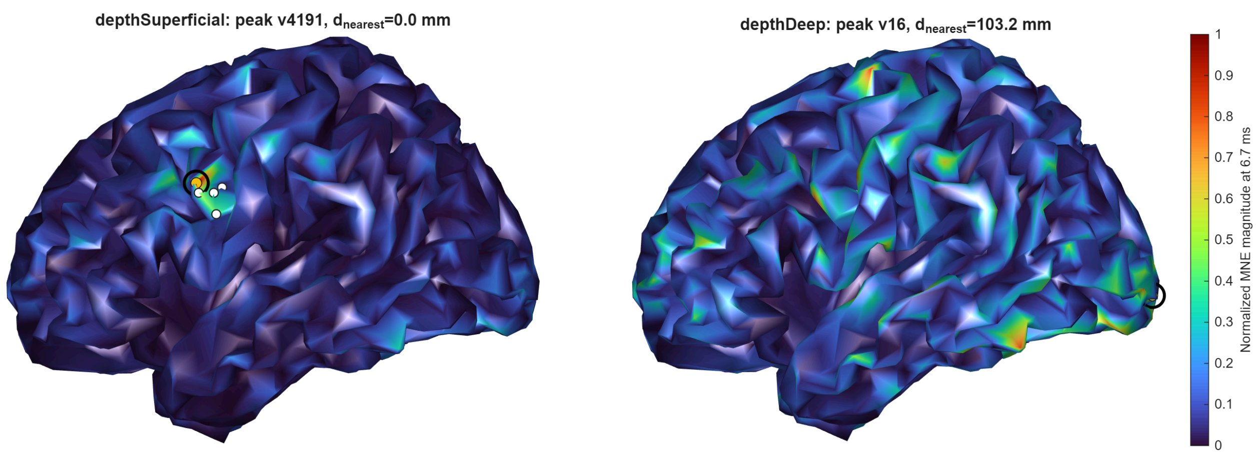

Figure 8: MNE source localization at the spike peak for the depth experiment. The superficial scout localizes correctly onto the scout, with peak at vertex 4191, whereas the deep scout localizes to vertex 16, more than `103 mm` from the nearest active theoretical vertex.

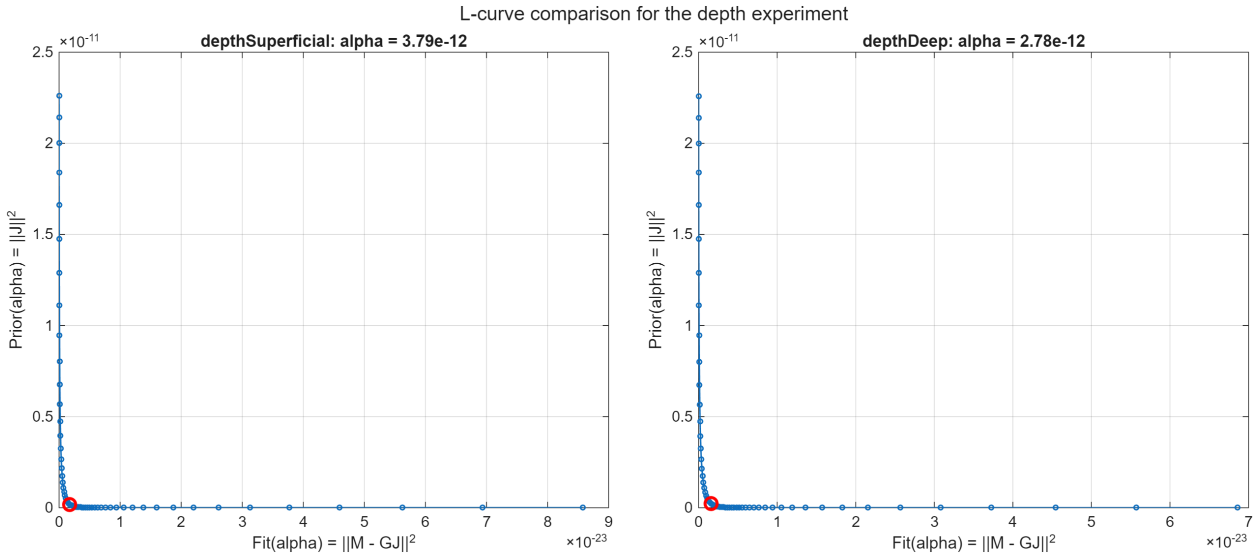

Figure 9: L-curve comparison for the depth experiment. The normalized cost selected was $\alpha = 3.79 \cdot 10^{-12}$ for the superficial source and $\alpha = 2.78 \cdot 10^{-12}$ for the deep source.

After fixing the source parameterization, the depth experiment now behaves in a way that is much closer to theory. The deeper scout generates a weaker MEG field, a much broader reconstructed map (`69` vertices above `50%` of the peak), and it failed at localizing. This is consistent with the depth bias of unweighted minimum-norm and with the reduced sensitivity of MEG to deeper cortical generators.

2.3. Experiment 3: Effect of source spatial extent

Case	Scout vertices	Best alpha	Peak |MEG| (T)	Vertices $\geq 50\%$ max	Localization error (mm)
`extentSmall`	`5`	`3.79e-12`	`7.91e-13`	`3`	`5.52`
`extentLarge`	`20`	`7.08e-12`	`1.11e-12`	`9`	`8.18`

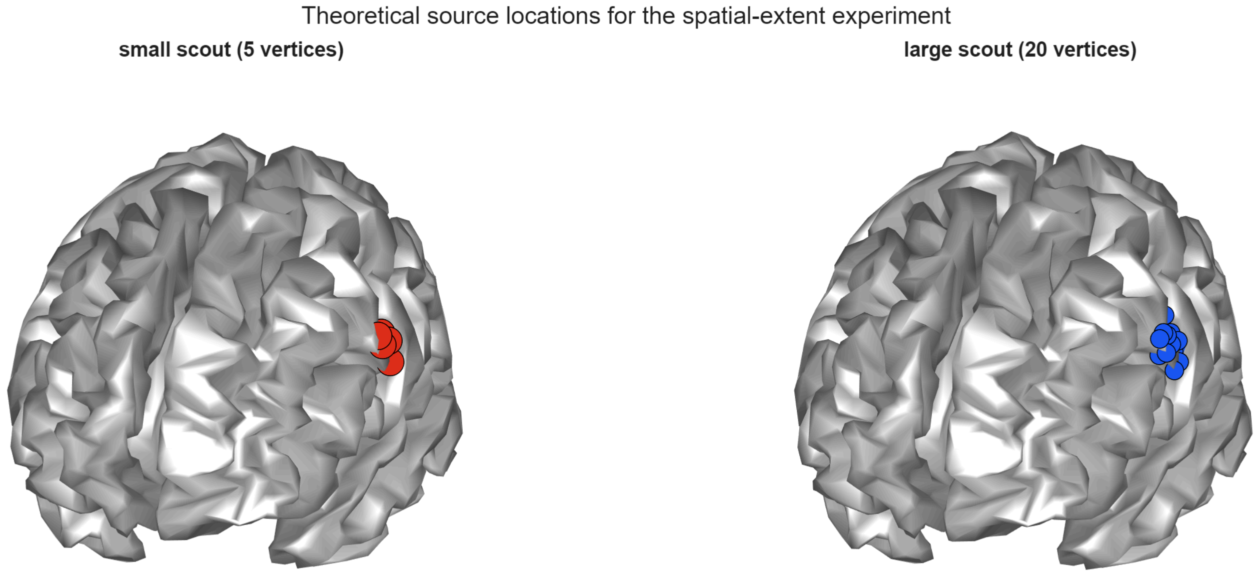

Figure 10: Theoretical source locations used for the spatial-extent experiment. The small case uses a 5-vertex superficial scout, whereas the large case uses a nearby 20-vertex superficial scout that fully contains the small scout.

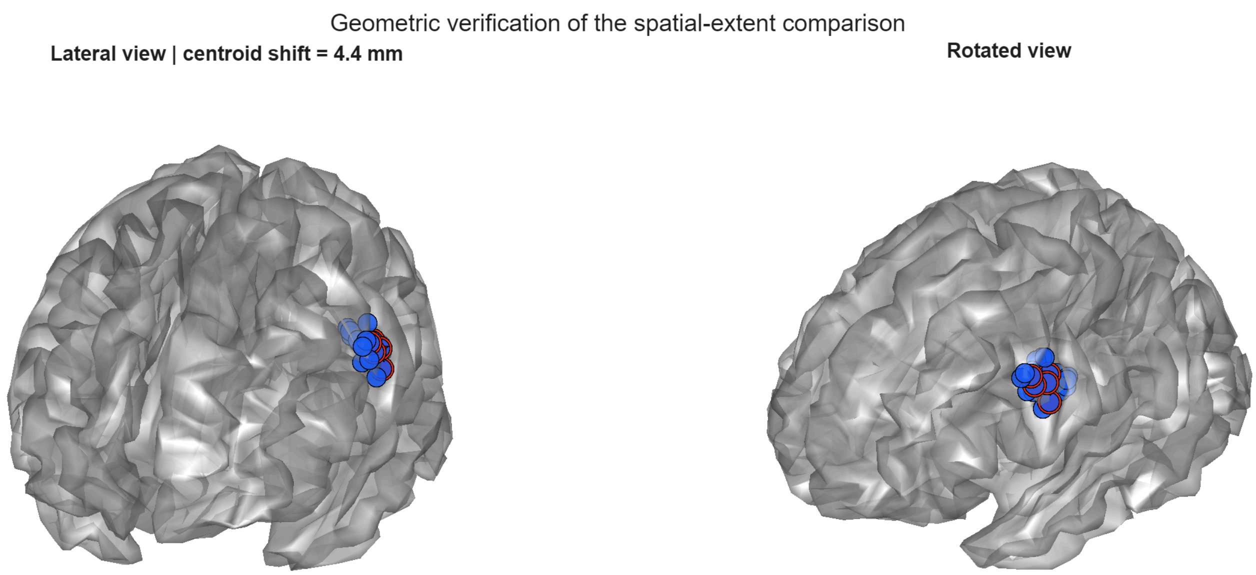

Figure 11: Geometric verification of the extent comparison. All `5` small-scout vertices overlap with the large scout, and the centroid shift between the two scouts is only `4.42 mm`.

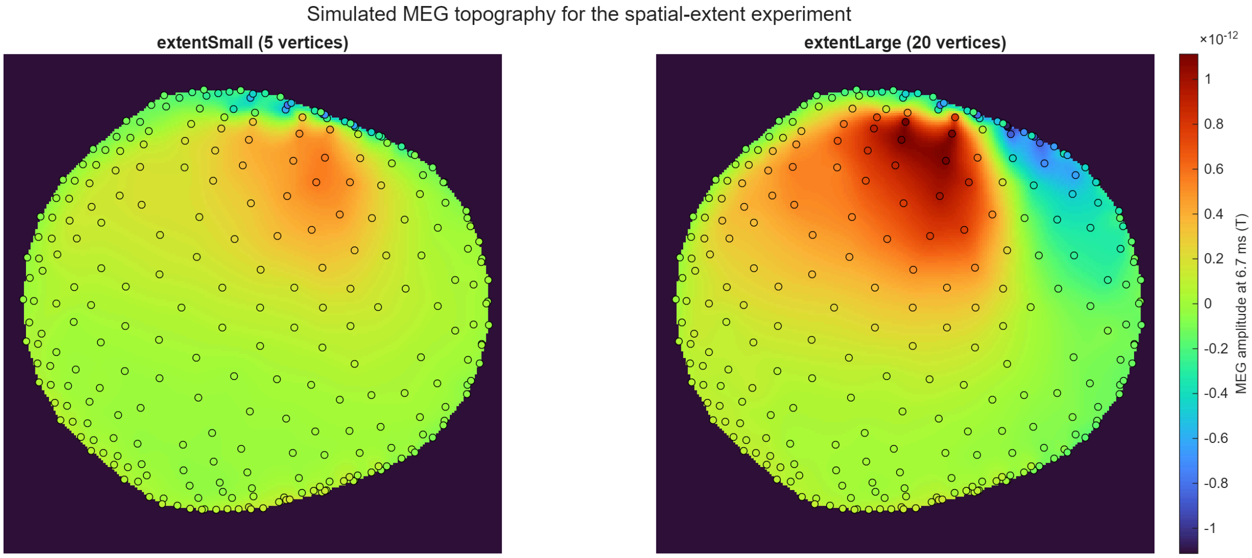

Figure 12: Simulated MEG topography at the spike peak for the spatial-extent experiment. The 20-vertex scout produces a stronger and broader sensor-level field than the 5-vertex scout, with peak absolute MEG amplitude increasing from `791 fT` to `1.11 pT`

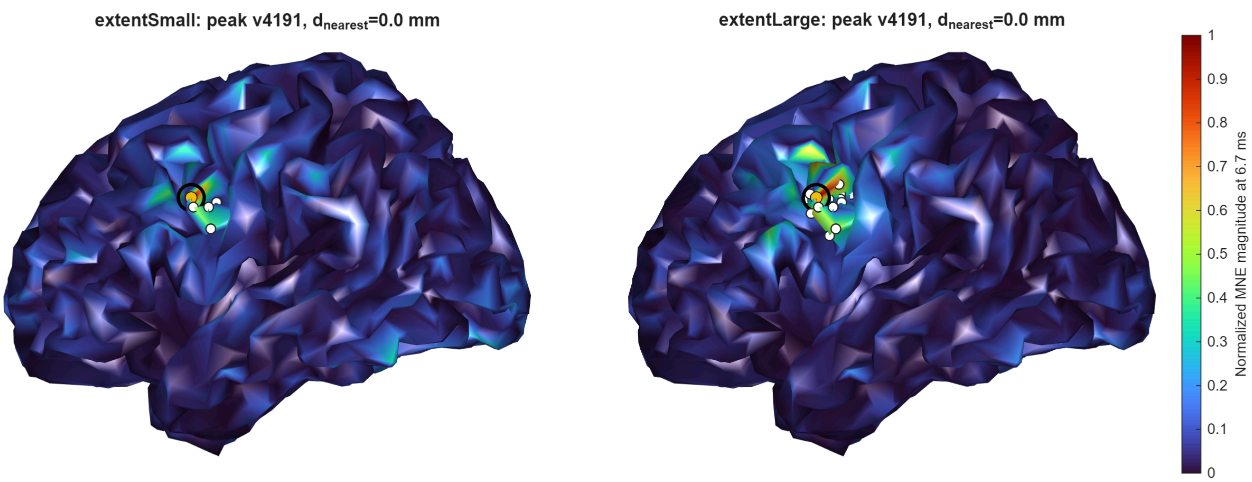

Figure 13: MNE source localization at the spike peak for the small and large superficial scouts. In both cases the dominant estimated vertex is `4191` which is one of the active theoretical scout vertcies. The larger scout produces a broader reconstruction around the shared peak.

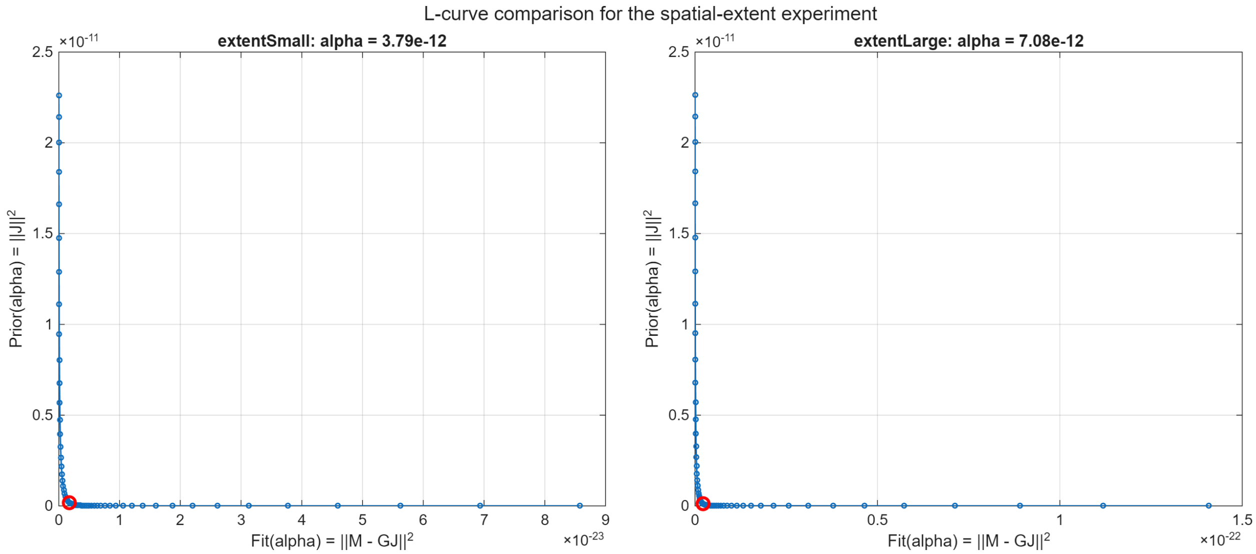

Figure 14: L-curve comparison for the extent experiment. The larger scout shifted the selected regularization parameter upward from 3.7910^{-12} to 7.0810^{-12}.

The extent experiment also became more plausible after the source-model correction. Both conditions localize to the correct cortical neighborhood, but the larger scout has a broader reconstructed patch (`3` to `9` vertices above `50%` of the peak).

The main caveat is the same, however. This can't be treated as an extent-only change because each active vertex is assigned the same amplitude. Increasing the number of active vertices therefore increases both the spatial extent and the total simulated source strength. That explains the larger MEG field and part of the increase in the selected α. Even so, the corrected MNE solution now shows a more intuitive extent effect than before, with the broader scout producing a broader cortical estimate around the same dominant peak.

3. Conclusion

The MNE with L-curve regularization was implemented and the final implementation used one scalar source amplitude per cortical vertex on the `white_6000V` mesh. This correction made the inverse solution consistent with the simulated scouts.

With the corrected pipeline, the noise and spatial-extent experiments localize to the expected cortical patch, and the dominant estimated vertex coincides with an active theoretical scout vertex in all superficial cases. The deeper scout, however, produces a weaker MEG field, a much broader estimate, and a localization failure. That behavior is in line with the expected depth sensitivity limitations of MEG and the superficial bias of unweighted MNE.

Overall, the final results are much more consistent and the implementation now shows the actual strengths and weaknesses of MNE.

4. Appendix A: MATLAB implementation

The core of the final implementation is shown below, the lead field is first projected onto the cortical normals so that each scout vertex corresponds to one scalar source location, then standard MNE with the L-curve is applied.

```
G = constrain_gain_to_surface_normals(Gfull, GridOrient);

alphaScale = trace(G * G') / nDipoles;
alphaList = alphaScale * logspace(-6, 2, 60);

Fit = zeros(size(alphaList));
Prior = zeros(size(alphaList));
Jall = cell(size(alphaList));

GGt = G * G';
Imeg = eye(size(GGt));

for k = 1:numel(alphaList)
  alpha = alphaList(k);
  Jcand = G' * ((GGt + alpha * Imeg) \ Msimul);
  Jall{k} = Jcand;
  Fit(k) = norm(Msimul - G * Jcand, "fro")^2;
  Prior(k) = norm(Jcand, "fro")^2;
end

cost = Fit ./ max(Fit) + Prior ./ max(Prior);
[~, iBest] = min(cost);
J = Jall{iBest};
```