Supplemental Information

This supplemental information contains technical information about the analyses presented in the main paper.

Participant MRI

The participants in the study had a structural MRI. The MRI data were collected on a ….; and other details of the structural MRI, T1W and T2W. The scans had 1 mm³ resolution and sufficient FoV to cover from the top of the head down to the neck.

Localization of External Fiducials and Electrode Fiducials

A Polhemus digitizer was used to locate in 3D space external scalp fiducial points and electrode fiducial points. The scalp fiducials were a set of external head locations used for the 10-10 system (Nz, Iz, LMA, RMA, LPA, RPA, Vz). These were digitized and the 3D coordinates saved. We also digitized the location of some “electrode fiducials” for the electrode generation. These were located on the Hydrocel Geodesic Sensor Net 128 (HGSN128) net near the fiducials (Nz-17, Oz-75, LMA-57, RMA-100, LPA-44, RPA-115, Vz-129).

External head measurements were done on each participant. The measures include semi-circumferences (front and rear sides-circumference from LMA to RMA, top circumferences from Nz to Iz, and from LMA to RMA) and lateral diameters (Nz to Iz, LMA to RMA).

Electrode Locations on MRI

The MRIcron program (Rorden, http://www.mccauslandcenter.sc.edu/mricro/mricron/) was used to display MRIs and do editing work. A set of fiducials were located on each MRI, including the anterior commissure, posterior commissure and a set of external head locations.
used for the 10-10 system (e.g., Nz, Iz, LMA, RMA, LPA, RPA, Vz). These locations were identical to the ones measured with the digitizer.

Average electrode placement locations were available that were constructed on age-appropriate average MRI template from the Neurodevelopmental MRI database (Richards et al., 2015a; Richards & Xie, 2015). The average electrodes were constructed from individual participants who had the positions of the HGSN 128 channel electrode net determined on the head. The electrode positions on the individuals were transformed to the average MRI template and averaged, and fitted to the average MRI template (Richards, 2015; Richards et al., 2015b).

The average electrode placements locations were transformed into the individual participant locations with the help of the external scalp fiducials and electrode fiducials. First, the digitized scalp fiducials were registered to the MRI scalp fiducials using “coherent point drift” registration (CPD version 2; Myronenko et al, 2006; Myronenko & Song, 2010). The resulting 12-degree of freedom affine registration matrix was used to transform the digitized electrode fiducials into the MRI space, thus giving the locations of the actual fiducial electrodes for each participant in MRI space. Second, the digitized-transformed electrode fiducial locations were then registered to the same electrodes on the age-appropriate average electrode placements with CPD. The registration matrix was then used to transform the average electrode placements into the participant space. This transformed electrode configuration was then fitted to the scalp by finding the nearest location to the scalp from the electrode. The resulting electrode locations were referenced to the AC-coordinate system for that participant. The CPD registration / transformation resulted in the digitized and transformed electrode fiducials being nearly in the exact same space, and presumably the average electrode configuration also was placed in the
appropriate space with this method (see Richards, 2015, and Richards et al., 2015a for details of these procedures).

**Supplemental Information in Richards (2013)**

We rely on methods presented in Richards (2013), both the main text and the supplemental information for that study. The following sections include details found either in the Supplemental Information or the main paper for that study.

**Head Segmentation** The materials in the head were segmented, including scalp, skull, CSF, white matter, gray matter, nasal cavity, and eyes (Richards, 2002, 2005, 2013). The gray matter was used as the source volume for the analysis.

**Atlases** Three atlases were constructed on the individual participants MRIs. The LONI Probabilistic Brain Atlas (LPBA40; Shattuck, et al., 2008) and the Hammers atlas, based on MRIs from the Information Exchange for the Internet (Hammers atlas; Heckemann, Hajnal, Aljabar, Rueckert, & Hammers, 2006; Heckemann, et al., 2003) were constructed on individual participants. Details of the construction of these atlases for individual participants may be found in Phillips et al. (2012) and Fillmore et al. (2015); and we have used these atlases in previous work to define ROIs for cortical source analysis (Guy, Zieber, & Richards, 2015; Richards, 2013; Xie & Richards, 2015; also see Supplemental Information for Richards, 2013). The LPBA40 atlas has 56 areas defined for the cortex, sub-cortex, brainstem, and cerebellum. The Hammers atlas has 83 areas defined from the cortex, sub-cortex, brainstem, and cerebellum. The third atlas was an automatically constructed lobar atlas that defined the major lobes (e.g., frontal, temporal) of the cortex, some sub-lobar cortical areas (e.g., fusiform gyrus), subcortical (e.g., striatum, thalamus), cerebellum and brainstem. This atlas was constructed from a manually-labeled age-appropriate lobar atlas transformed into the participant’s MRI space, the adult MRI average
template lobar atlas transformed into the participant space, and the relevant segments from the LPBA and Hammers atlas. These atlases were combined with a majority vote procedure to define a lobar atlas for each individual MRI.

We also used two atlases based on an age-appropriate atlas for each participant. The “Harvard-Oxford” (cite) and Brodmann (cite) atlases were used from the FSL computer program. These atlases were transformed from the MNI152 atlas used in the FSL computer program to age-appropriate atlases. This atlas, now in the age-appropriate template space, was further transformed into the participant space.

The atlases were used to define several anatomical areas by identifying common designations from each of the atlases, and ROIs were mapped for each participant MRI. These ROIs are listed in the main paper, and show in Figure 1 of the main paper. They were chosen based on theoretical grounds or previous research examining ERN components brain areas in adult participants. The primary ones of interest were the orbital-frontal gyrus, ventral anterior cingulate, dorsal anterior cingulate, and ventral-lateral inferior frontal gyrus. Additionally, we used other ROIs that could account for ERP activity that might not be specifically related to the ERN effects. These include the parietal lobe, intraparietal sulcus, frontal pole, dorsolateral prefrontal cortex, and motor and premotor areas. Supplemental Information Table 2 has a list of the ROIs The label in that table are for the anatomical areas taken from the lobar, Hammers, LPBA40, or Harvard-Oxford atlas, or are the Brodmann areas.

**EMSE Source analysis** Source analysis was conducted with realistic head models and the current density reconstruction (CDR) technique to determine the cortical activity in the ROIs. This was done both with the EMSE’s Data Analysis module (Source Signal) and the Fieldtrip computer program. First, the electrode locations, source locations, and head
model generated in the previous procedures were used with EMSE’s Data Analysis (Source Signal, Inc) to estimate the forward model and inverse model. The realistic cortical source models used an FEM mapping of the electrical conductivity of the head to calculate the forward model. The forward model was used to estimate a lead-field matrix. This lead-field matrix estimation was based on the locations of the electrodes on the scalp, the source locations defined by the segmented GM and the location of the eyes, and the FEM model for the individual participant. Second, cortical activity was estimated as the current source density of cortical source locations with the CDR technique and the sLORETA (Pascual-Marqui, 2002; Pascual-Marqui, Michel, & Lehmann, 1994) as the constraint for the CDR. The ERP data surrounding the N1 and ERN peaks was used to estimate the CDR volumes. The resulting values were a source map of amplitude vectors (CDR moments) that was transformed into a power value. Thus for every cortical source location there was a current density at that location, the sum of which would generate the scalp-recorded EEG.

**Fieldtrip Source Analysis**

The Fieldtrip (citation) computer programs were used for source analysis. The FT programs are a set of procedures for MATLAB that do segmentation, head model generation, and source analysis. They use both custom programs and integrate MRI programs from other sources (e.g., SPM, BESA, FreeSurfer). The following steps were used to generate the head models and do the source analysis. Custom MATLAB macros were used in each step that took account of the computer-storage organization of the author; however a brief min-script for each FT call is presented.

1—**Create a MRI information file.** The first step was to create a information file describing the MRI. This was used for some of the programs, and to align the MRI space into AC-defined
The file saved the AC, PC, external scalp fiducials, and the MRI dimensions. (i.e., mrinfo structure with ac, pc, nz, iz, …. xdim, ydim, zdim).

2—Electrode files. The electrode placement files were read from the placement locations above and save in the FT format (i.e., a elec structure, with elecpos, chanpos, unit, label).

3—Source grid files. The gray matter segmentation was used to construct the locations of sources for the current density reconstruction. The gray matter segmentation was used to construct the locations of sources for the current density reconstruction. The eyes were also included (cf. Richards, 2015, adolescents). This was done by loading the gray matter partial volume estimates, and the segmented eyes locations, and aligning the volume to the AC-defined space (ft_volumerealign). A 3mm grid was then created from the resulting MRI volume (ft_prepare_sourcemodel, ft_determine_coordsys). The grid positions (grid.pos) were then used to map to the coordinates of a MRI and this MRI was also saved. We also created a 1mm grid for each participant and a 1mm MRI of the source locations. Figure nn shows the grid with the electrodes plotted about the grid positions.

4—Head models. We created both Boundary Element Method (BEM) and Finite Element Method (FEM) head models. These were done from the segmentation of the MRI. For the BEM model, the outer scalp, skull, CSF, and brain were constructed into a 4-compartment MRI. The compartments were modified slightly so each inner compartment was contained in all the outer compartments (scalp skull CSF brain) and this volume was realigned to the AC-defined space (ft_volumerealign). A mesh was created for each compartment using “projectmesh” and 2000 vertices (ft_prepare_mesh). Figure nn shows the resulting mesh plotted with the electrodes on the edges of the mesh. The four meshes, conductivity, and tissue names were then used to create a “DIPOLI” (citation) BEM model (ft_prepare_headmodel). For the FEM model, the full
segmented head was used. The tissue types

({'wm','gm','t2wesf','dura','skull','scalp','head','eyes','nasal cavity'}) and the MRI voxel values
were loaded into a FT MRI volume, and aligned to the AC-defined space (ft_volumerealign).

The head model was used to create a wireframe mesh with hexahedral
volumes.(ft_prepare_mesh). The mesh and conductivity values were used to create a “SIMBIO”
citation) FEM model (ft_prepare_headmodel).

5—Lead-field matrices. The leadfield matrices were created with electrodes, source model, and
head model (ft_prepare_leadfield). A leadfield matrix was created for each model (BEM-
DIPOLI, FEM-SIMBIO).

6—Source reconstruction—CDR reconstructions The source reconstructions were done with
exact-LORETA (eLORETA). The lead field matrices exist for BEM and FEM models, and each
with a eLORETA source reconstruction. The leadfield matrices and ERP data files are loaded
and the source reconstruction is done (ft_sourceanalysis). The resulting amplitude vector (CDR
moment) was transformed into a power value. Thus for every location in the source model grid a
power value was obtained representing the current density at that location needed to generate the
scalp ERP (given the head model and source inverse restraint).

Anatomical ROIs and CDR-per-mm in ROI, and Estimated MRI Volumes

The source reconstructions from both EMSE and Fieldtrip were used to get the sum (and mean)
CDR per mm for each ROI. The MRI segmented anatomical atlases were transformed from
segmented MRI volumes into a series matrix values for the segmented atlas voxel type and atlas
position. The segmented atlas positions were then used to identify each position in the CDR
matrix, and sum the CDR values across the entire ROI. The mean CDR per mm was computed
as the summed CDR divided by the number of grid points making up that atlas segment. Thus for
each msec of the ERP data put into the model, we have the CDR values for each ROI in our atlas segments.

In addition to the CDR values for each atlas ROI segment, I also created a simulated MRI volume based on the CDR values. This was done with the ft_sourceinterpolate programs. This program maps the grid position of each CDR value into the coordinates of a MRI and assigning the voxel value as the CDR value for that grid position. This was done for the original resolution (3mm), and also for an interpolated 1mm MRI volume using spline interpolation.
References


Fieldtrip Macros

Realign MRI volumes to AC-defined space

cfg=[];
cfg.method='fiducial';
cfg.landmark.ac=mriinfo.ac;
cfg.landmark.pc=mriinfo.pc;
cfg.landmark.xzpoint=mriinfo.vertex;
cfg.landmark.right=mriinfo.rpa;
cfg.coordsys='spm';
cfg.parameter='gray';
mri=ft_volumerealign(cfg,mri);

Create the source model grid

cfg=[];
cfg.mri=mri;
cfg.threshold=.25;
cfg.smooth='no';
cfg.elec=elec;
cfg.grid.resolution=mmresol; %1 mm or 3 mm
cfg.grid.unit='mm';
grid = ft_prepare_sourcemodel(cfg,mri);
grid=ft_determine_coordsys(grid,'interactive','no')

Create a compartment volume mesh

cfg = [];
cfg.method = 'projectmesh';
cfg.tissue = 'gray';
cfg.numvertices = 2000;
mesh = ft_prepare_mesh(cfg, mri);

Prepare the BEM-DIPOLI head model

cfg = [];
cfg.feedback = false;
cfg.method = 'dipoli';
cfg.isolatedsource = 'no';
cfg.conductivity = [conductivity(6) conductivity(5) conductivity(3) conductivity(2)];
cfg.tissue = {'scalp','skull','csf','gray'};
vol = ft_prepare_headmodel(cfg,mesh);

Prepare the FEM mesh

cfg = [];
cfg.shift = 0.3;
cfg.method = 'hexahedral';
mesh = ft_prepare_mesh(cfg,mri);
Prepate the BEM-SIMBIO head model

cfg = [];  
cfg.method = 'simbio';  
cfg.conductivity = conductivity;  
vol = ft_prepare_headmodel(cfg, mesh);

Prepare the lead-field matrix

cfg = []  
cfg.vol = vol;  
cfg.elec = elec;  
cfg.grid = grid;  
cfg.normalize = 'no';  
lf = ft_prepare_leadfield(cfg);

MNE Source reconstruction

cfg = [];  
cfg.method = 'mne';  
cfg.vol = vol;  
cfg.elec = elec;  
cfg.grid = lf;  
cfg.projectnoise = 'yes';  
cfg.keepcsd = 'yes';  
cfg.mne.projectnoise = 'yes';  
cfg.mne.keepcsd = 'yes';  
cfg.mne.lambda = .000001;  
cfg.mne.prewhiten = 'no';  
sourcemne = ft_sourceanalysis(cfg, ERPdata);

eLORETA source reconstruction

cfg = [];  
cfg.method = 'eloreta';  
cfg.vol = vol;  
cfg.elec = elec;  
cfg.grid = lf;  
cfg.projectnoise = 'yes';  
cfg.keepcsd = 'yes';  
cfg.eloreta.projectnoise = 'yes';  
cfg.eloreta.keepcsd = 'yes';  
cfg.eloreta.lambda = 1e-5;  
cfg.lambda = cfg.eloreta.lambda;  
sourceft = ft_sourceanalysis(cfg, centermean);
Table 2. Regions-of-interest (ROIs) and anatomical regions with labels from the lobar, Hammers, LPBA40, Harvard-Oxford, and Brodman atlases. The left column are lateralized, and are presented from posterior-anterior and lateral-medial. The right column are bilateral and presented from posterior to anterior.

<table>
<thead>
<tr>
<th>Lateral inferior frontal gyrus</th>
<th>Frontal pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPBA40</td>
<td>Harvard-Oxford</td>
</tr>
<tr>
<td>25, 26 Inferior frontal gyrus (L,R)</td>
<td>Frontal pole</td>
</tr>
<tr>
<td>Hammers</td>
<td>LPBA40</td>
</tr>
<tr>
<td>56, 57 Inferior frontal gyrus (L,R)</td>
<td>29,30 Middle orbitofrontal gyrus</td>
</tr>
<tr>
<td>Brodman</td>
<td>33,34 Gyrus rectus</td>
</tr>
<tr>
<td>47 Inferior frontal gyrus</td>
<td>Hammers</td>
</tr>
<tr>
<td>Insula</td>
<td>53, 53 Straight gyrus</td>
</tr>
<tr>
<td>Insula</td>
<td>68,69 Medial orbital gyrus</td>
</tr>
<tr>
<td>Lobar Insula</td>
<td>121,122 Cingulate gyrus</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dorsolateral prefrontal cortex</th>
<th>Frontal pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPBA40</td>
<td>LPBA40</td>
</tr>
<tr>
<td>101,102 Insular cortex (L,R)</td>
<td>121,122 Cingulate gyrus</td>
</tr>
<tr>
<td>Hammers</td>
<td>Hammers</td>
</tr>
<tr>
<td>20,21 Insula (L,R)</td>
<td>76,77 Subgenual anterior cingulate</td>
</tr>
<tr>
<td>Brodman</td>
<td>78,79 Subcallosal area</td>
</tr>
<tr>
<td>9, 46 Dorsolateral prefrontal cortex</td>
<td>24,25 Cingulate gyrus, anterior (supragenual)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frontal eye fields</th>
<th>Frontal pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPBA40</td>
<td>LPBA40</td>
</tr>
<tr>
<td>6, 8 Premotor, frontal eye fields</td>
<td>121,122 Cingulate gyrus</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Precentral and postcentral gyrus</th>
<th>Frontal pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPBA40</td>
<td>LPBA40</td>
</tr>
<tr>
<td>27,28 Precentral gyrus (L,R)</td>
<td>24,24 Cingulate gyrus, anterior (supragenual)</td>
</tr>
<tr>
<td>41,42 Postcentral gyrus (L,R)</td>
<td>Posterior cingulate cortex (Posterior to AC)</td>
</tr>
<tr>
<td>Hammers</td>
<td>LPBA40</td>
</tr>
<tr>
<td>50,51 Precentral gyrus (L,R)</td>
<td>121,122 Cingulate gyrus</td>
</tr>
<tr>
<td>60,61 Postcentral gyrus (L,R)</td>
<td>Hammers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Superior parietal lobe</th>
<th>Frontal pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPBA40</td>
<td>26, 27 Cingulate gyrus, posterior part</td>
</tr>
<tr>
<td>43,44 Superior parietal gyrus(L,R)</td>
<td></td>
</tr>
<tr>
<td>Hammers</td>
<td>62,63 Superior parietal gyrus(L,R)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Supramarginal gyrus</th>
<th>Frontal pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPBA40</td>
<td>45,46 Supramarginal gyrus (L,R)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angular gyrus</th>
<th>Frontal pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPBA40</td>
<td>47,47 Angular gyrus</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intraparietal sulcus</th>
<th>Frontal pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>3mm border between inferior parietal lobe (LPBA40 SMG, AG; Hammers Remainder of parietal cortex) and superior parietal lobe (LPBA40 and Hammers)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Hydrocel GSN 128 electrode positions on the structural MRI of a 14-year-old participant and the 14-year-old average MRI template.
Figure 2. Regions of Interest (ROIs) shown on a 14 Year Old MRI

- Dorsal anterior cingulate cortex
- Superior parietal lobe
- Frontal pole
- Orbital-frontal gyrus
- Ventral anterior cingulate cortex
- Posterior cingulate cortex
- Superior parietal lobe
- Intraparietal sulcus
- Supramarginal gyrus
- Angular gyrus
- Precentral and Postcentral gyri
- Intraparietal sulcus
Figure 3. EMSE Source model and Finite Element Method (FEM) Head model

EMSE Source Model Wireframe From 3 mm Grid from Fieldtrip

EMSE Finite Element Method Head model, with proportional conductivity per tetrahedron
Figure 4. The Fieldtrip source model, 2mm grid, with HGSN128 electrode locations

Axial view

Side projection
Figure 5. The Fieldtrip BEM (Boundary Element Method) Head mesh, with HGSN 128 electrodes
Figure 6. The Fieldtrip BEM (Boundary Element Method) Head model from DIPOLOI methods, with HGSN 128 electrodes
Figure 7. The Fieldtrip FEM (Finite Element Method) Head model from SIMBIO methods, with HGSN 128 electrodes.