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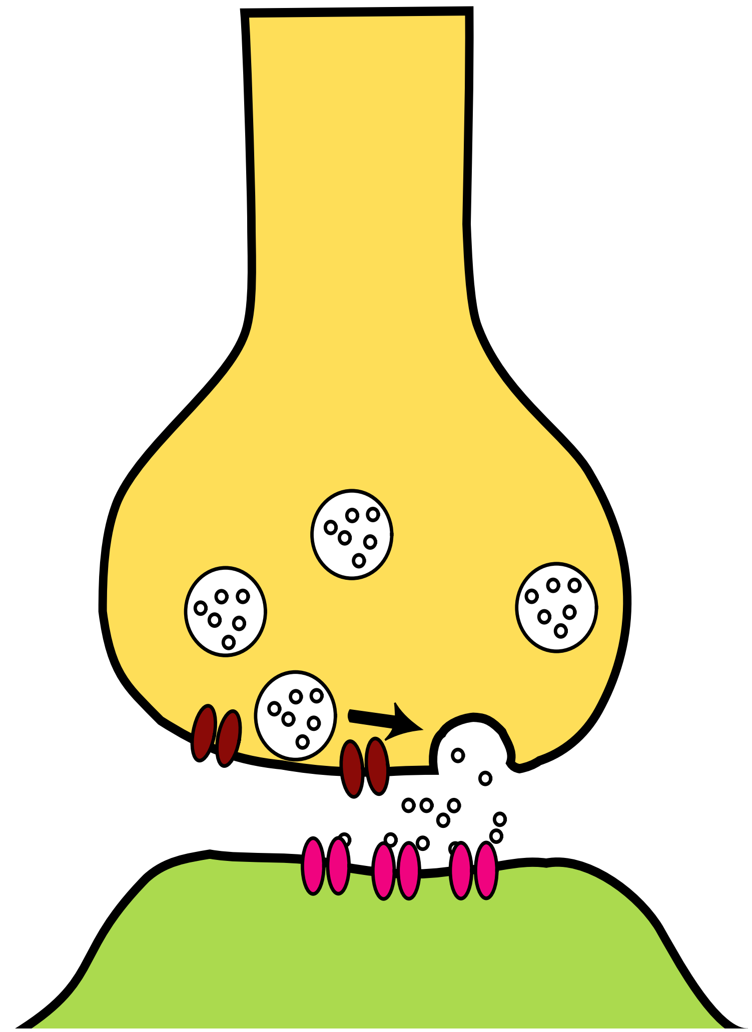
Generation & Propagation of ERPs

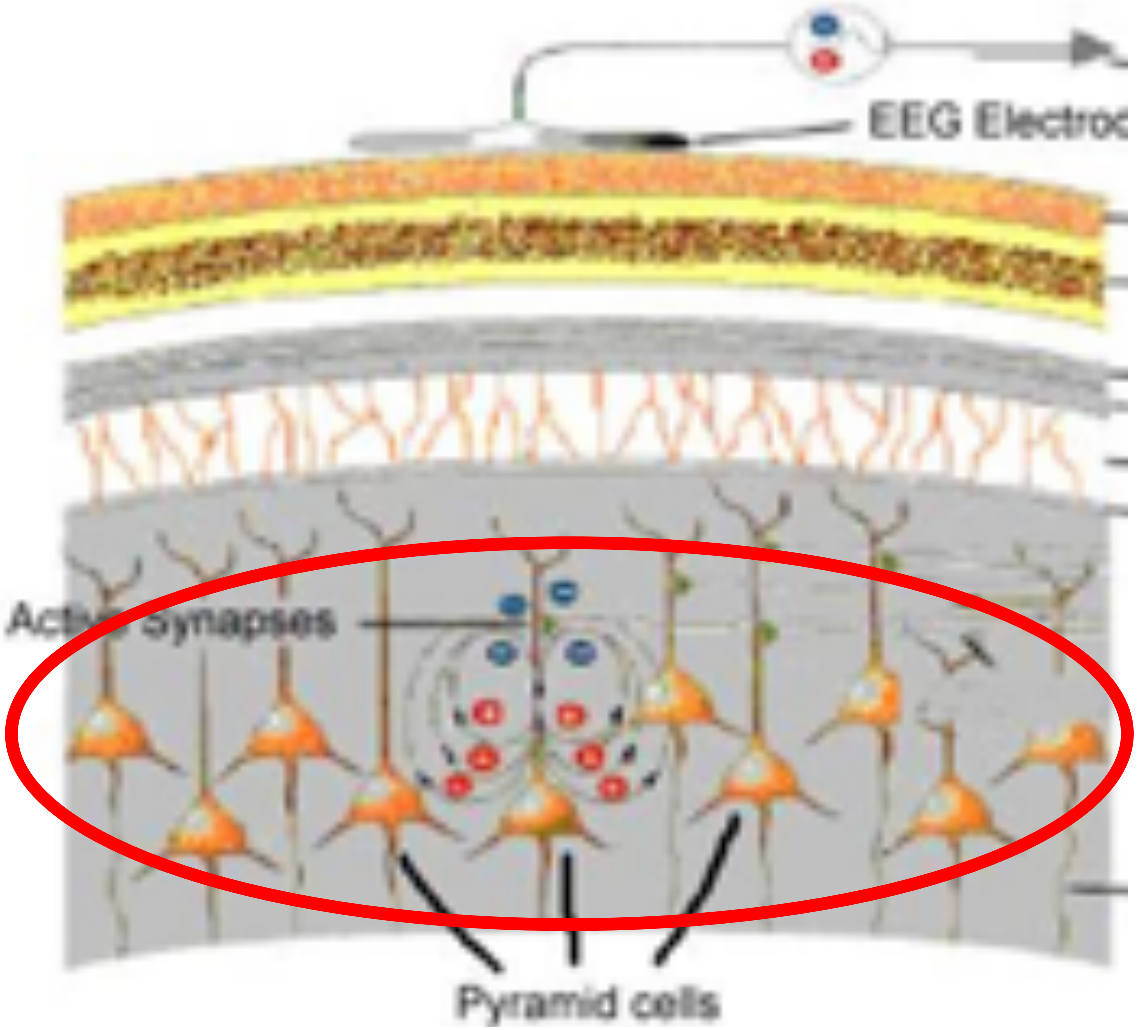
From Source to Scalp

Adapted from https://commons.wikimedia.org/wiki/File:Synapse_Illustration2_tweaked.svg

In almost all cases, ERPs are the result of the postsynaptic potentials that are produced during neurotransmission.

Except under extremely unusual circumstances, action potentials can’t be detected from the scalp.

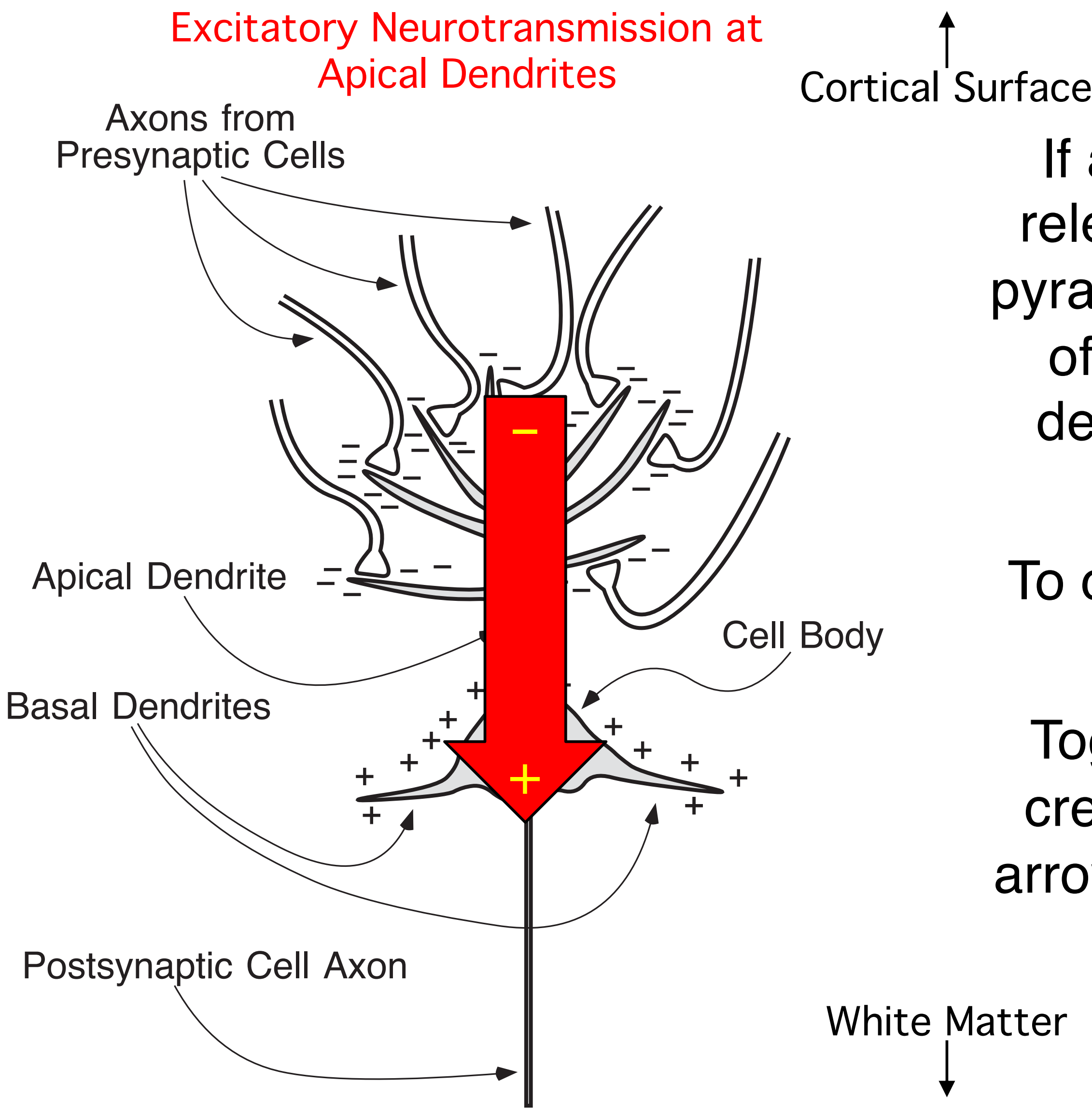




http://www.psych.nmsu.edu/~jkroger/lab/EEG_Introduction.html

Almost all ERPs arise from the pyramidal cells of the neocortex.

Pyramidal cells are the main input-output neurons of the cortex and are aligned perpendicular to the surface of the cortex.



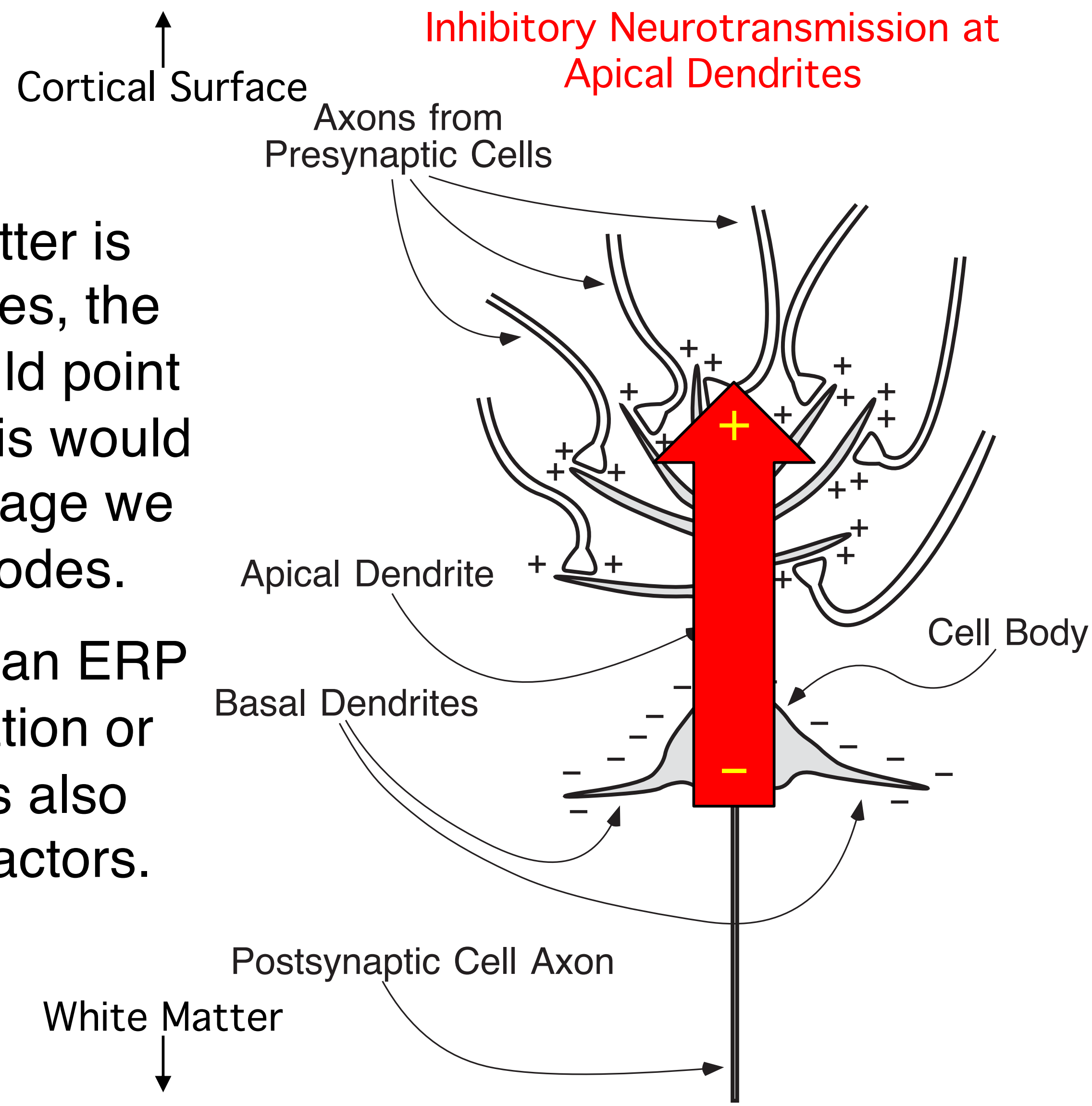
If an excitatory neurotransmitter is released at the apical dendrites of a pyramidal cell, this will lead to the flow of positively charged ions into the dendrites, creating a net negativity outside the dendrites.

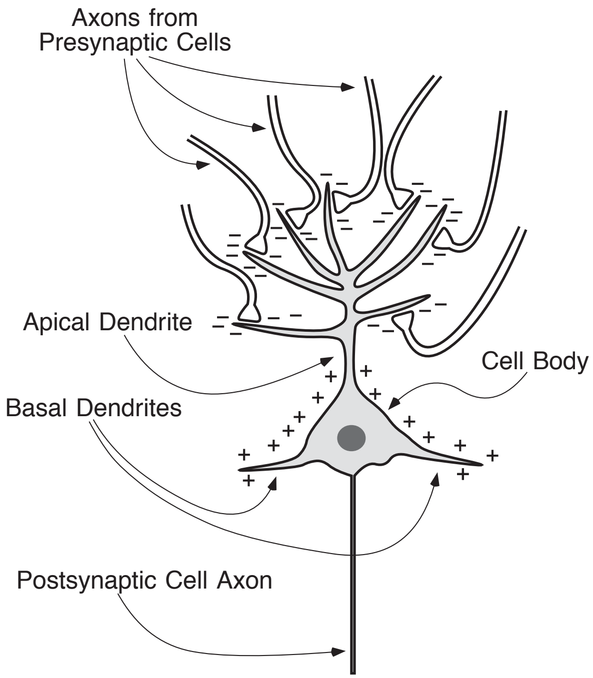
To complete the circuit, there is a net positivity near the cell body.

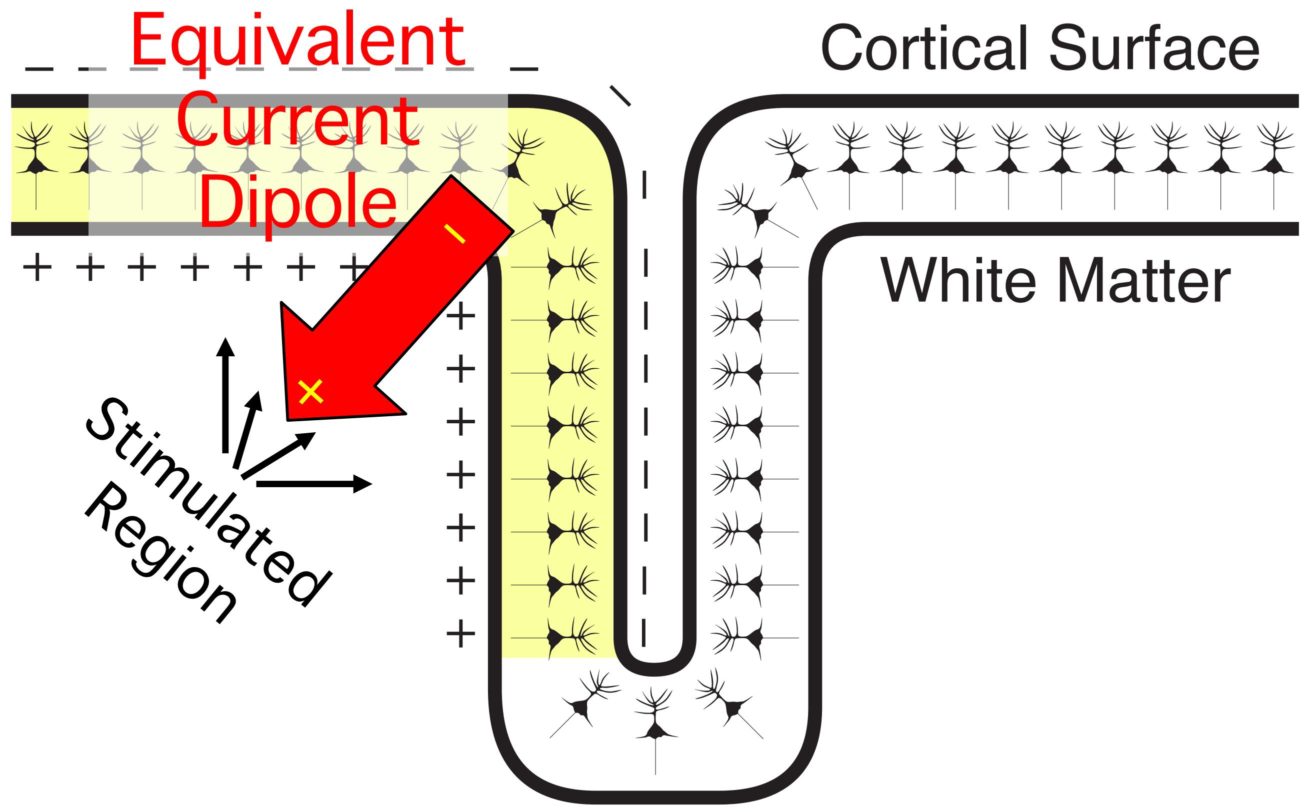
Together, the negative and positive create a small electrical dipole. The arrow head indicates the positive end.

If an inhibitory neurotransmitter is released at the apical dendrites, the positive side of the dipole would point toward the cortical surface. This would reverse the polarity of the voltage we record from our scalp electrodes.

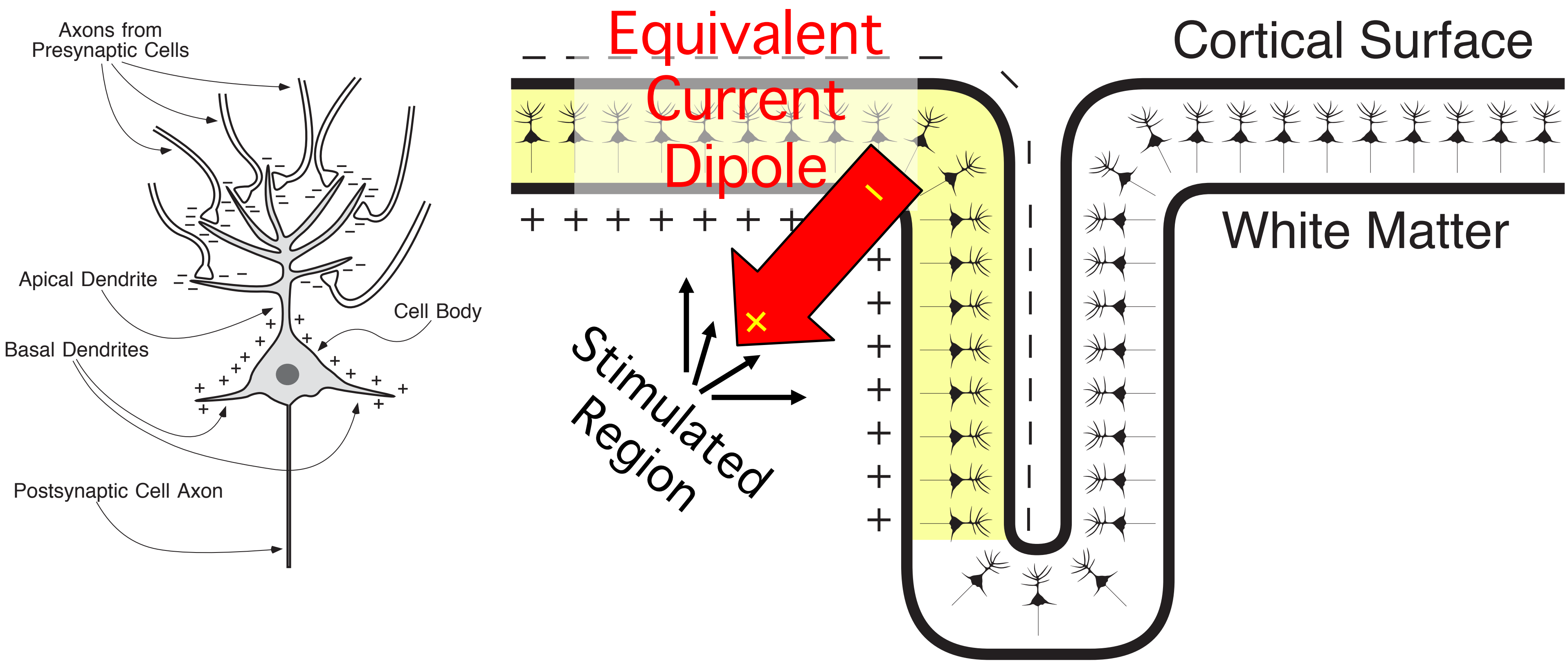
You cannot use the polarity of an ERP to distinguish between excitation or inhibition because polarity is also influenced by several other factors.

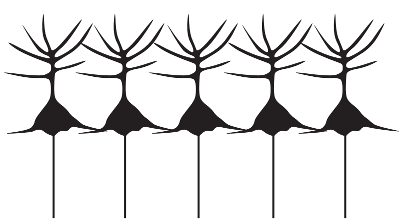




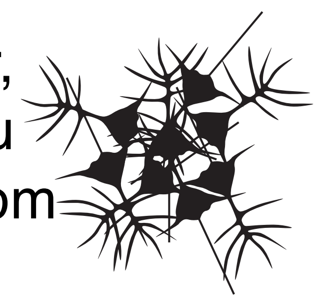


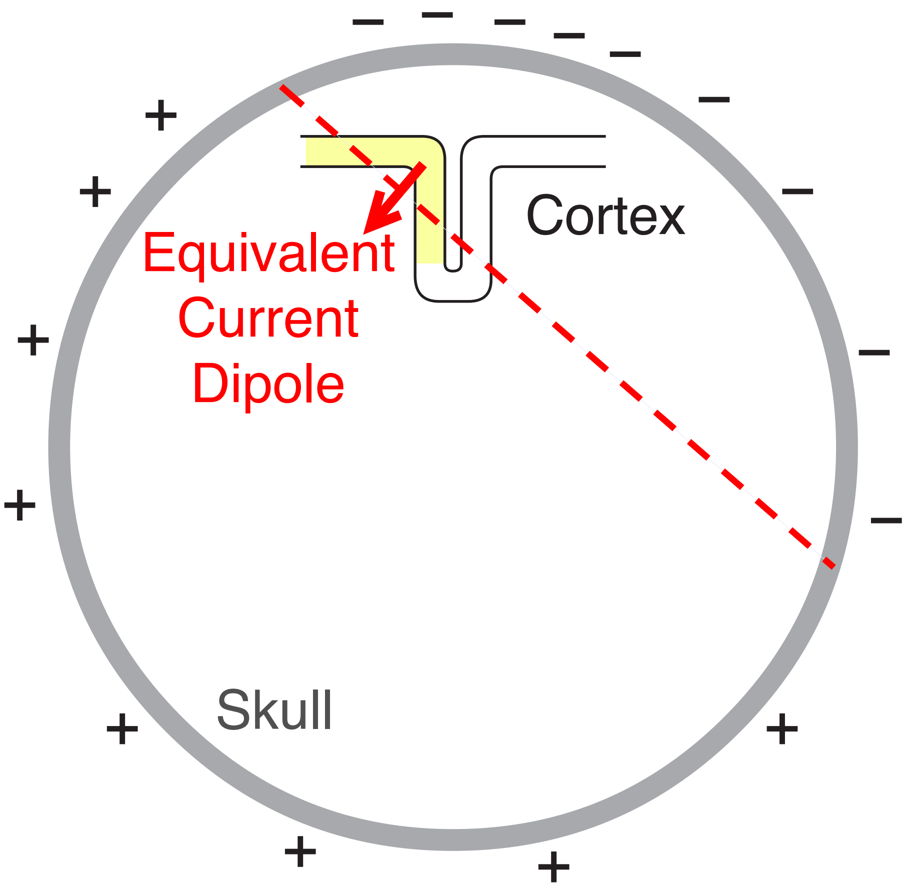
The dipoles from the individual neurons sum together, creating a voltage field that is indistinguishable from a single dipole that is equal to the sum of the individual-neuron dipoles. This is called an Equivalent Current Dipole.





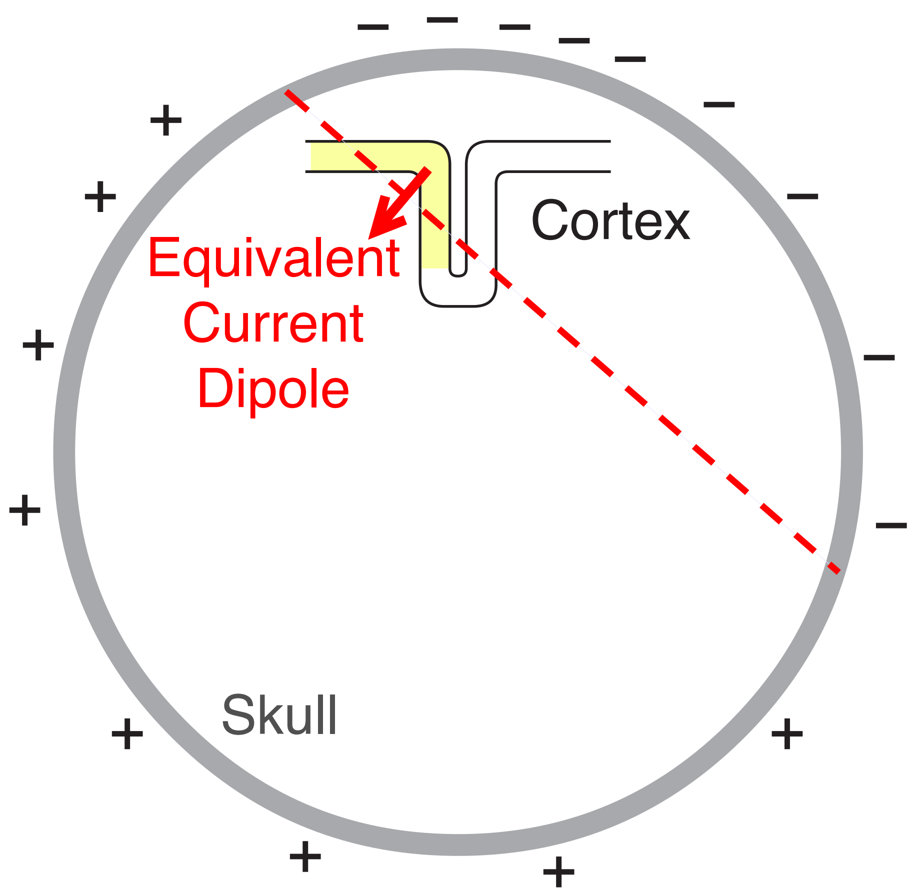
Cortical pyramidal cells are parallel to each other, allowing their dipoles to sum to a large value. You cannot ordinarily get ERPs from interneurons or from areas where the neurons are randomly oriented.



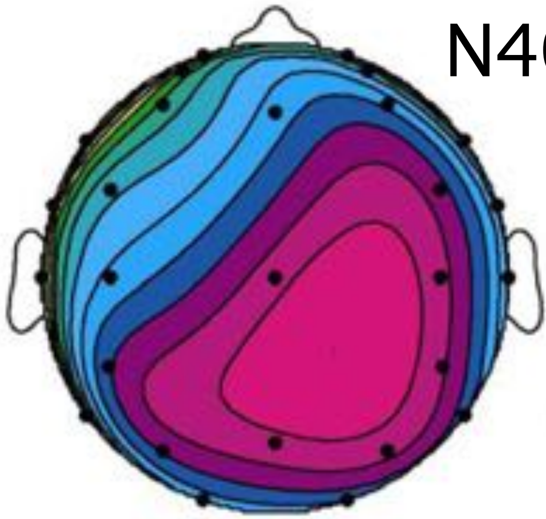


On the surface of the head, we have a negativity on one side of the dipole and a positivity on the other side.

The strength of the voltage varies from location to location, and there's a belt of zero voltage separating the negative and positive sides.



- Voltages are instantaneously conducted to the scalp
- The scalp voltages are the extracellular potentials generated by the neurons
- Voltage everywhere except at positive-negative transition
- Skull increases the amount of lateral spread



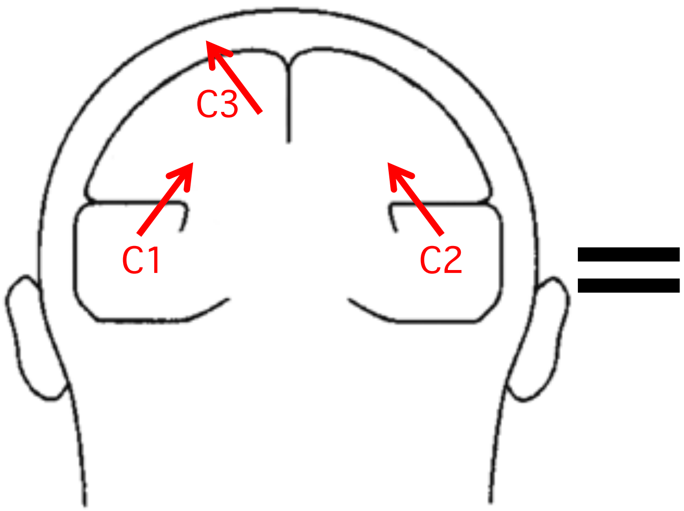
N400

In many cases, the electrode with the largest voltage is quite far away from the generator.

The N400 appears to be generated in the temporal lobes, but we see it on the scalp at the central and parietal electrodes.

Generation & Propagation of ERPs

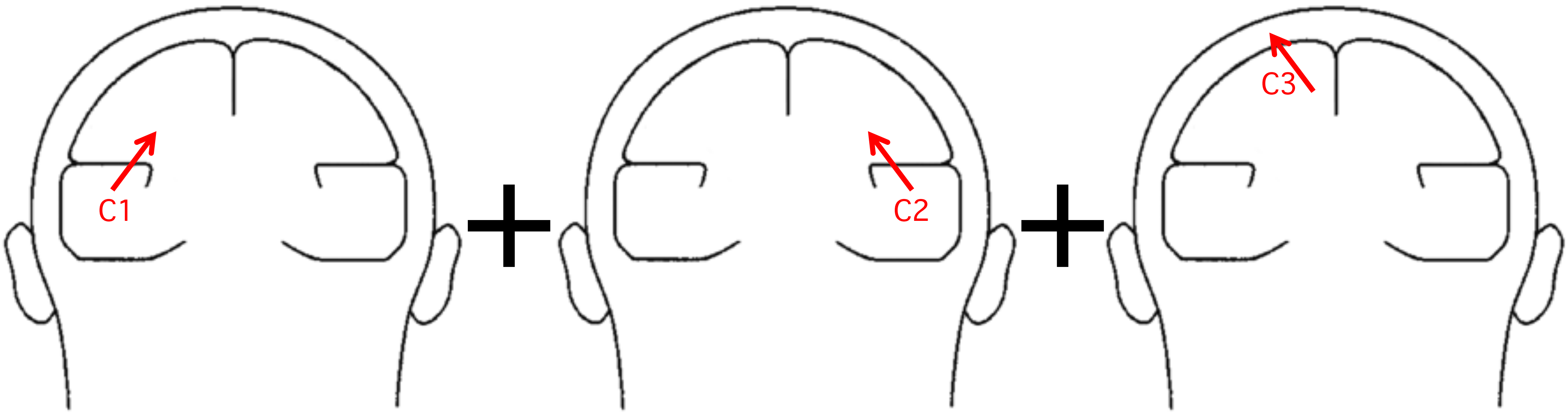
From Scalp to Source



When multiple voltages pass through a conductor at the same time, they simply sum together.

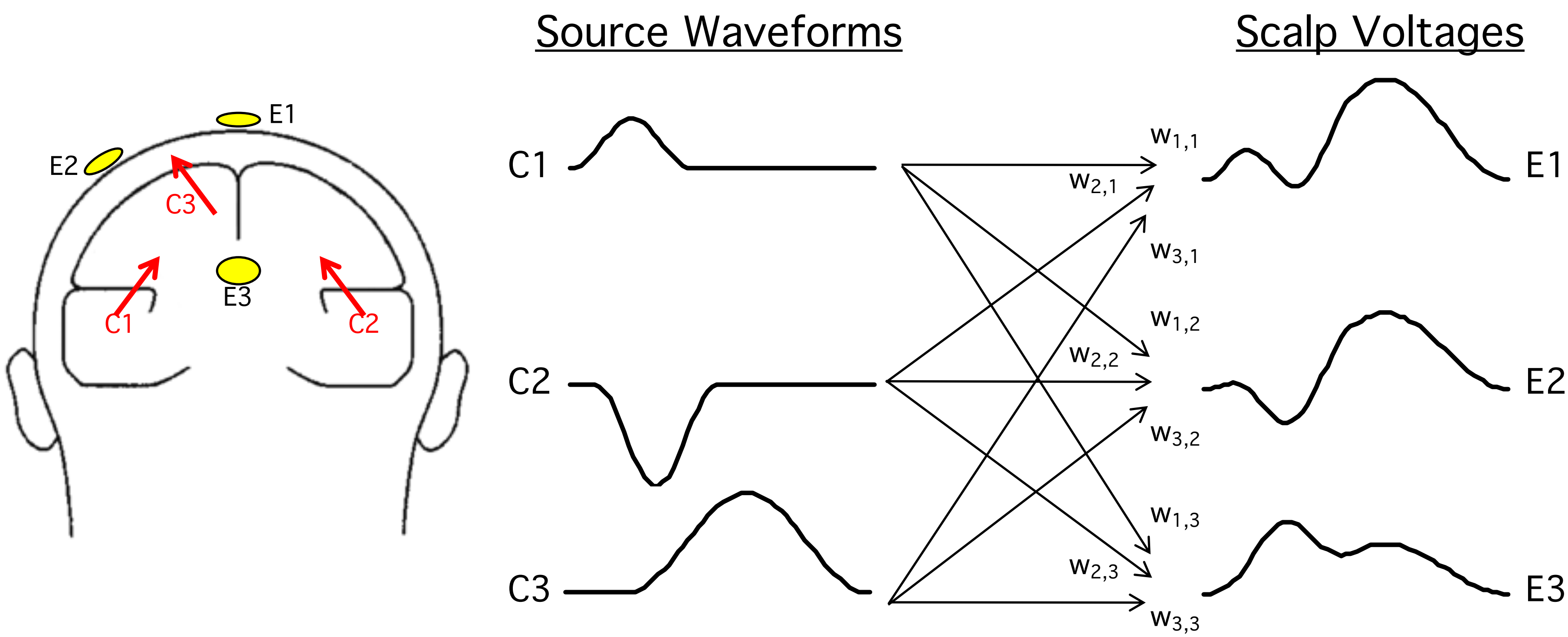
The scalp signals from these three generator sources when they’re present simultaneously is equal to the sum of the signals for each source alone.

As a result, the voltage at any given scalp electrode is simply a weighted sum of the underlying source waveforms.



The Superposition Problem

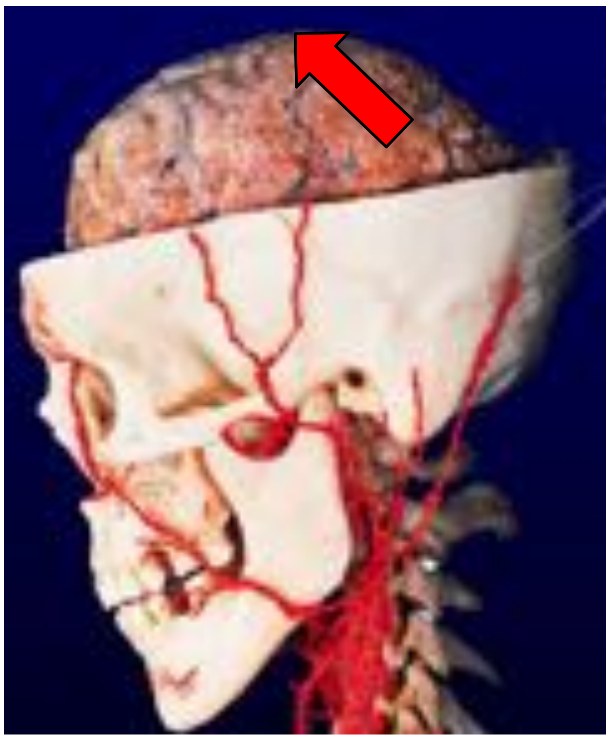
The voltages at a given electrode site are a mixture of the underlying sources.



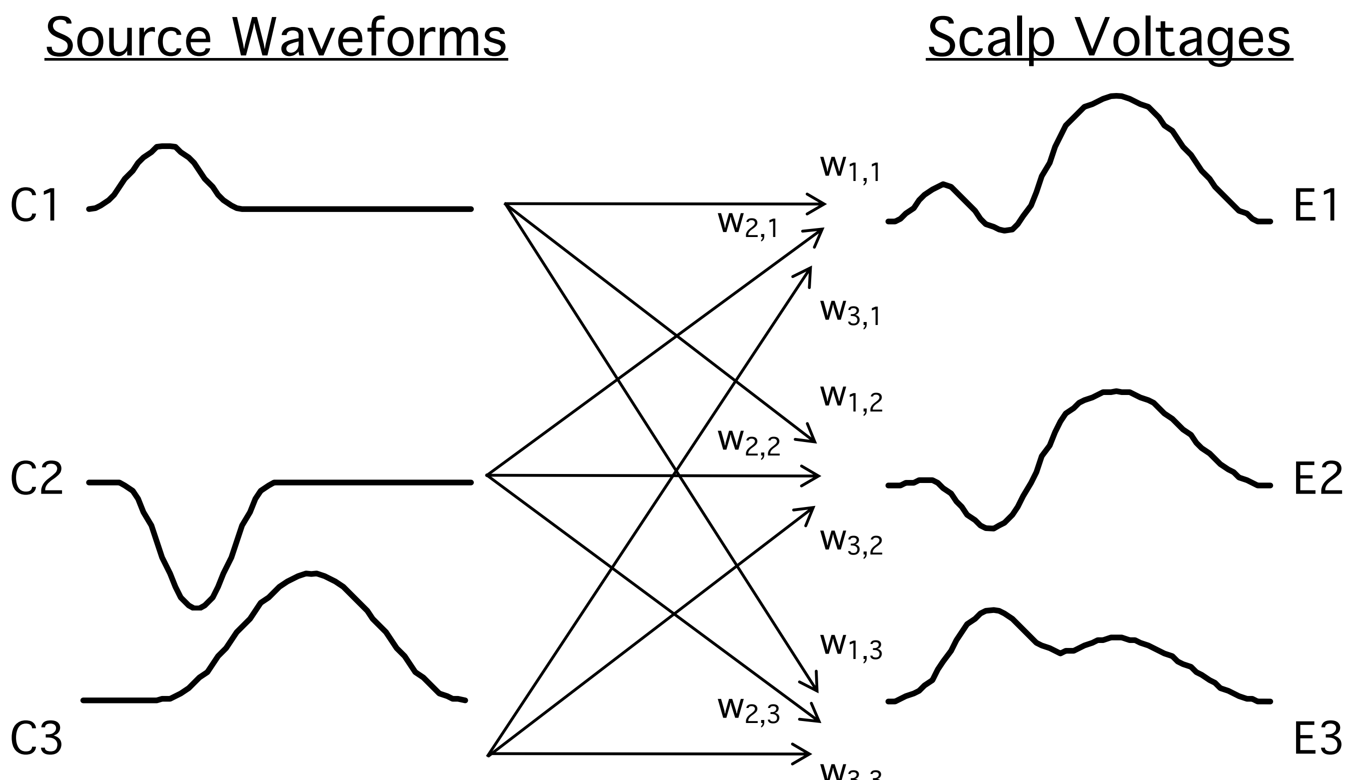
Note: These are arbitrary weights and may not match the actual weights for this combination of components and electrodes.

Mathematical Source Localization

The weighting between a given component and a given electrode depends on the location and orientation of the dipole, the location of the electrode, and the conductivity of the brain, meninges, skull, and scalp.

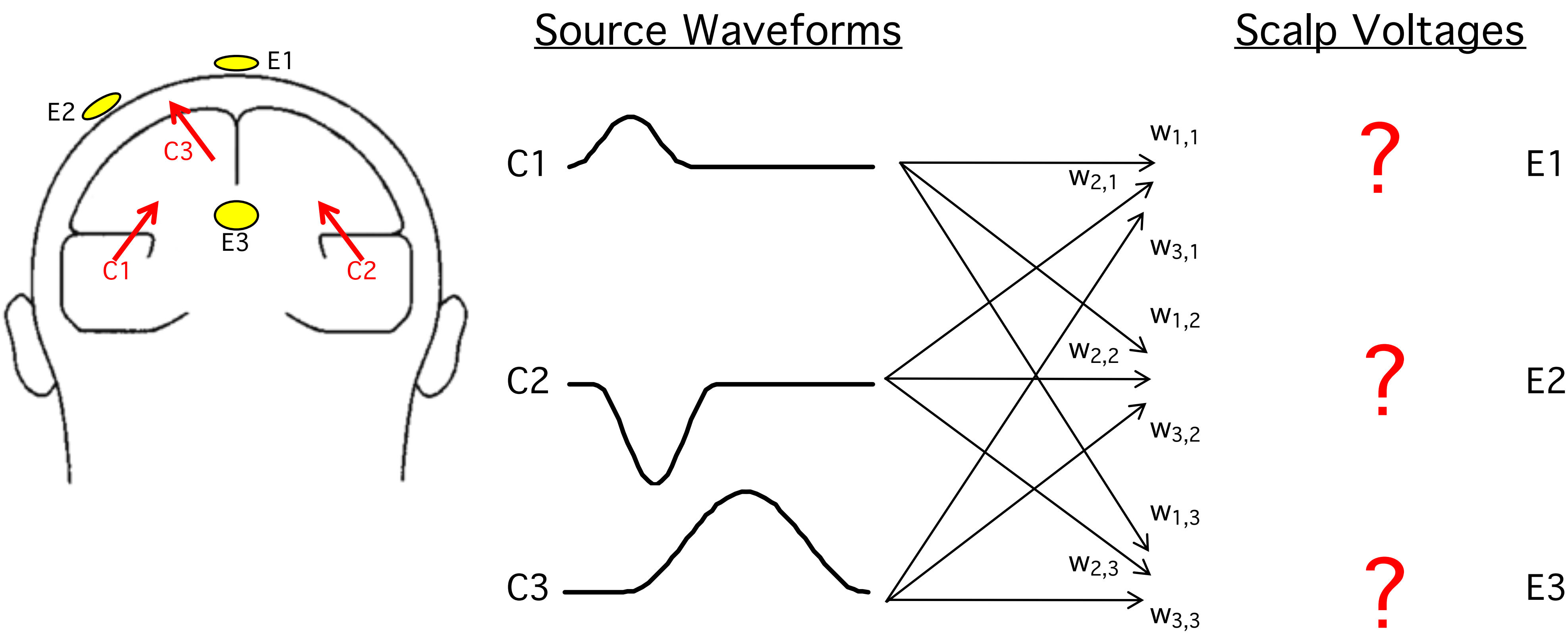


http://www.english.upenn.edu/~mamills/



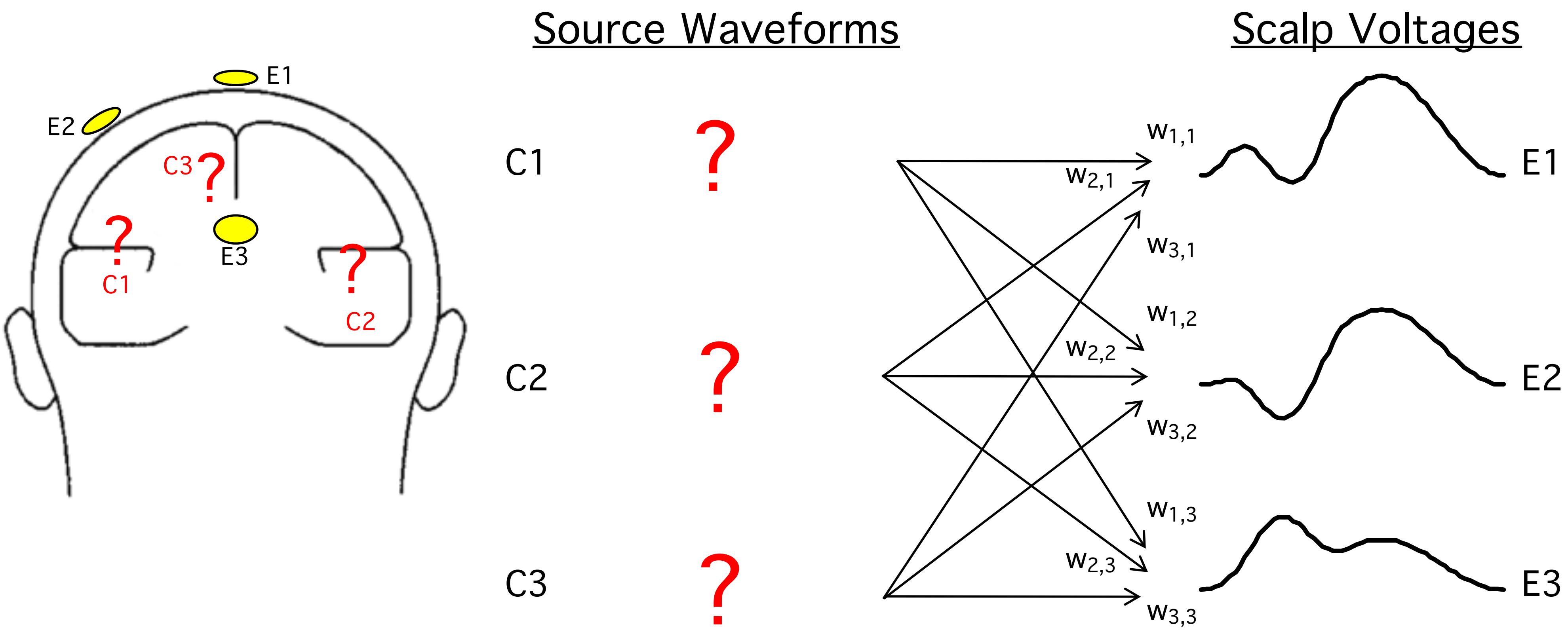
Note: These are arbitrary weights and may not match the actual weights for this combination of components and electrodes.

The Forward Problem: the problem of estimating the voltages in our scalp electrodes if we knew the locations, orientations, and source waveforms of the underlying components. Straightforward physics problem.



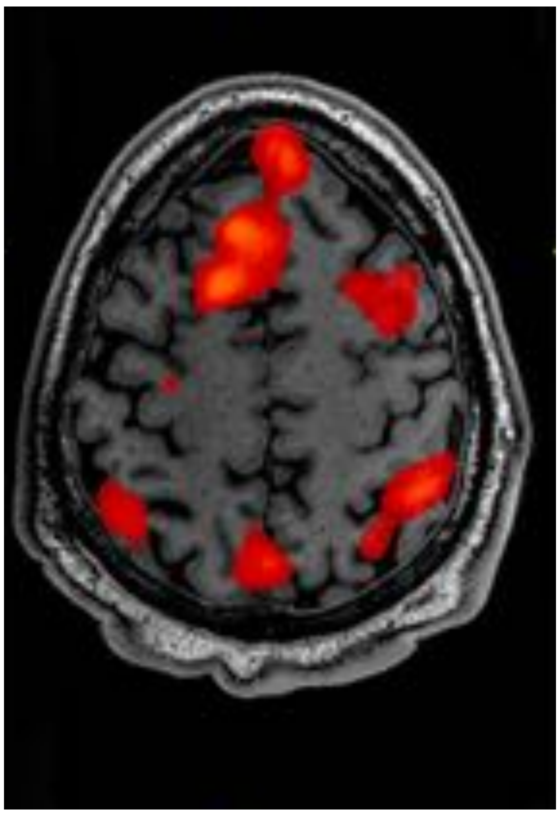
Note: These are arbitrary weights and may not match the actual weights for this combination of components and electrodes.

The Inverse Problem: the problem of estimating the locations and source waveforms of the underlying components when given the ERP waveforms from the scalp electrodes. An ill-posed problem (infinite # of solutions).



Note: These are arbitrary weights and may not match the actual weights for this combination of components and electrodes.

Not easy to combine fMRI and ERP data to get both spatial and temporal resolution. For example, ERPs are almost entirely a result of postsynaptic potentials, but the BOLD signal in fMRI is sensitive to anything that causes a change in blood oxygenation.



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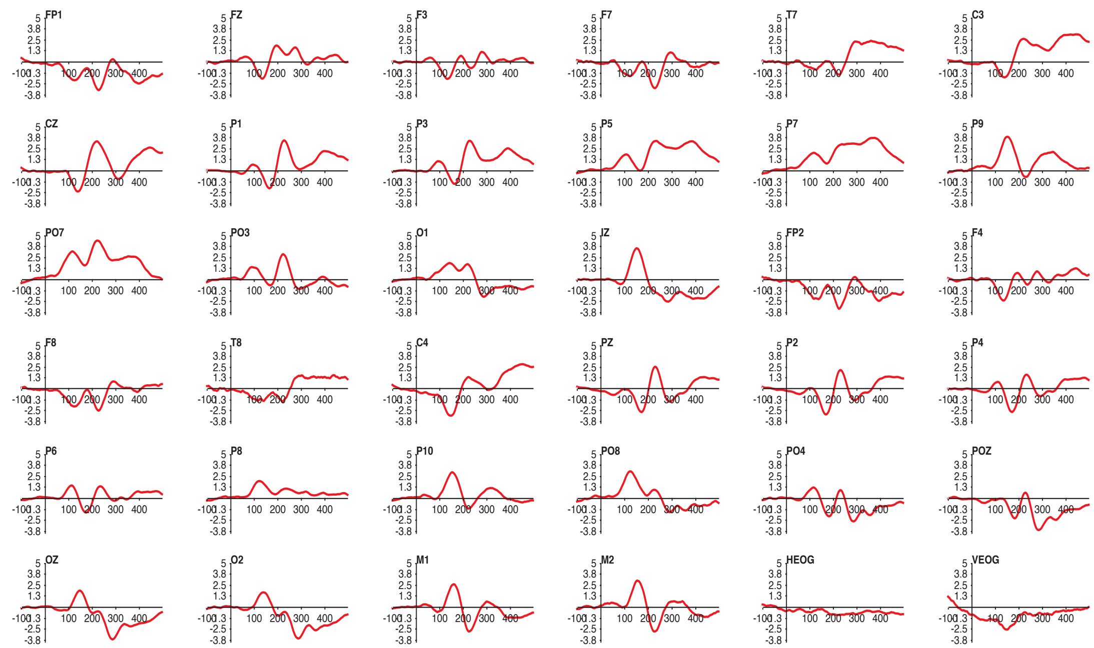


◆ Human Brain Mapping 8:115–120(1999) ◆

Direct and Indirect Integration of Event-Related Potentials, Functional Magnetic Resonance Images, and Single-Unit Recordings

Steven J. Luck*

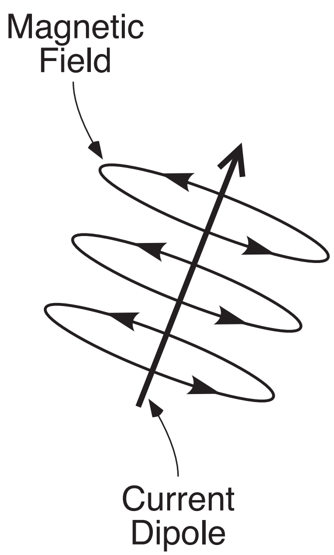
Department of Psychology, University of Iowa, Iowa City, Iowa

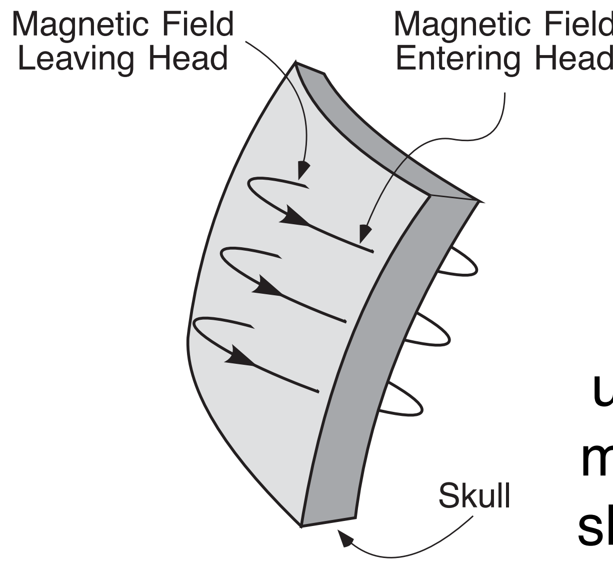
Abstract: Cognitive neuroimaging techniques vary along three primary dimensions: invasiveness, temporal resolution, and spatial resolution. Several of the major techniques excel on two of these three dimensions, but none of them excels on all three. In principle, multiple techniques with different strengths and weaknesses could be combined to obtain high temporal and spatial resolution data about human neural activity, and this article compares two approaches to combining microelectrode, hemodynamic, and electromagnetic measures of neural activity. The first approach involves using structural magnetic resonance images to provide a common reference frame for the mathematical estimation of neural activity, and the second approach involves parallel experimental manipulations and converging evidence. At present, neither approach is entirely satisfactory, and the integration of different measures of neural activity, therefore, requires a combination of direct and indirect approaches. *Hum.Brain Mapping 8:115–120, 1999.*

Key words: evoked potentials; ERPs; positron emission tomography; functional magnetic resonance imaging

Luck, S. J. (1999). Direct and indirect integration of event-related potentials, functional magnetic resonance images, and single-unit recordings. *Human Brain Mapping*, *8*, 115–120.

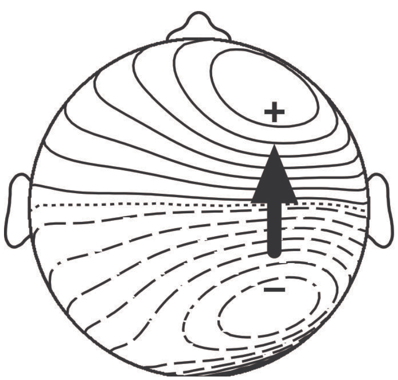
Magnetoencephalography (MEG)



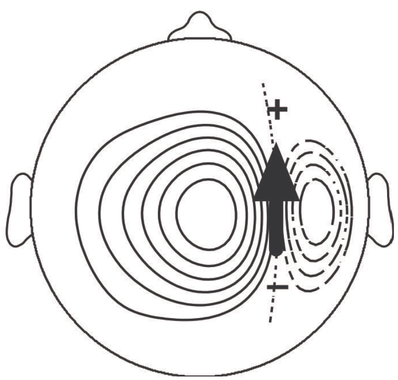


Whenever you have an electrical dipole, a magnetic field is running around it.

If a dipole lies right underneath the skull, the magnetic field will exit the skull and enter again, and the strength of this magnetic field will go up and down along with the EEG.



Electrical Potential



Magnetic Field

The magnetic field outside the head runs perpendicular to the electric field on the scalp.

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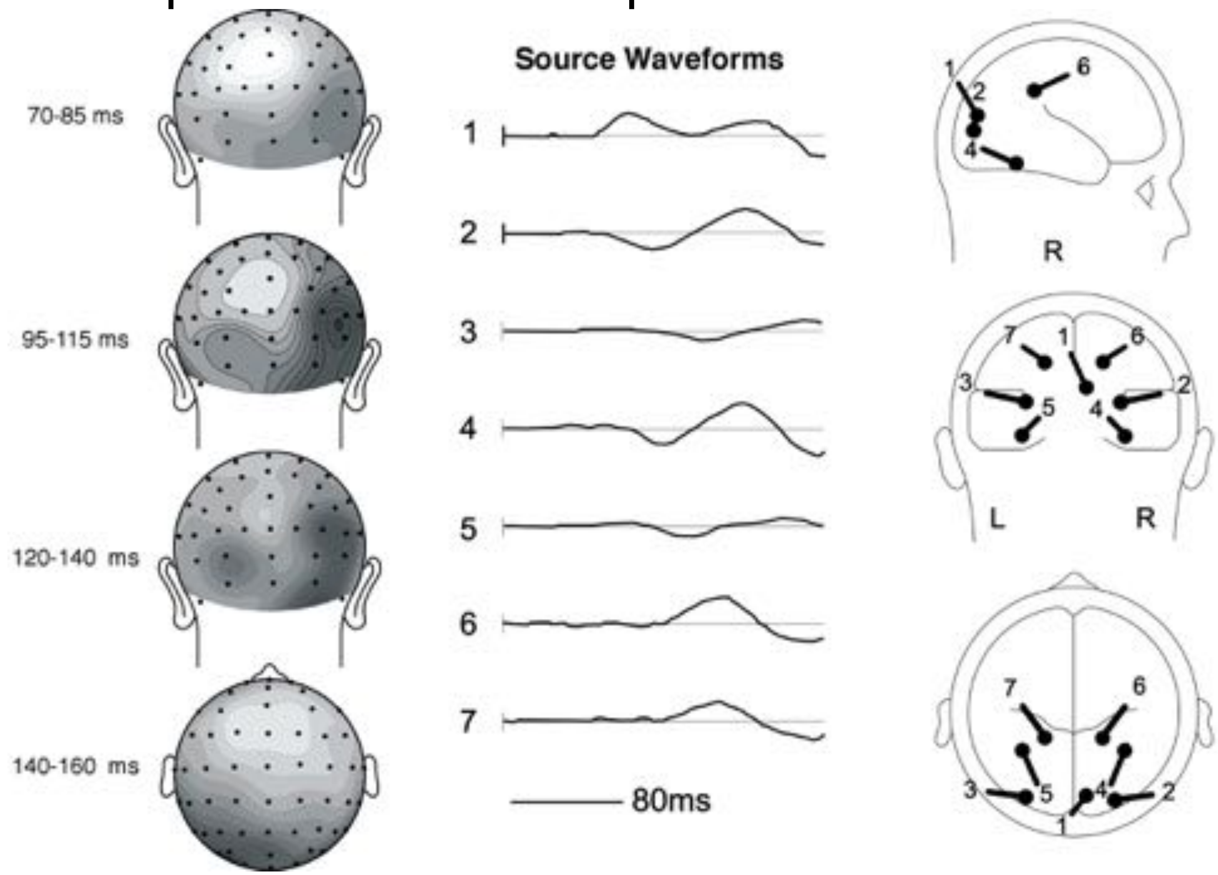
Generation & Propagation of ERPs

ERP Source Localization

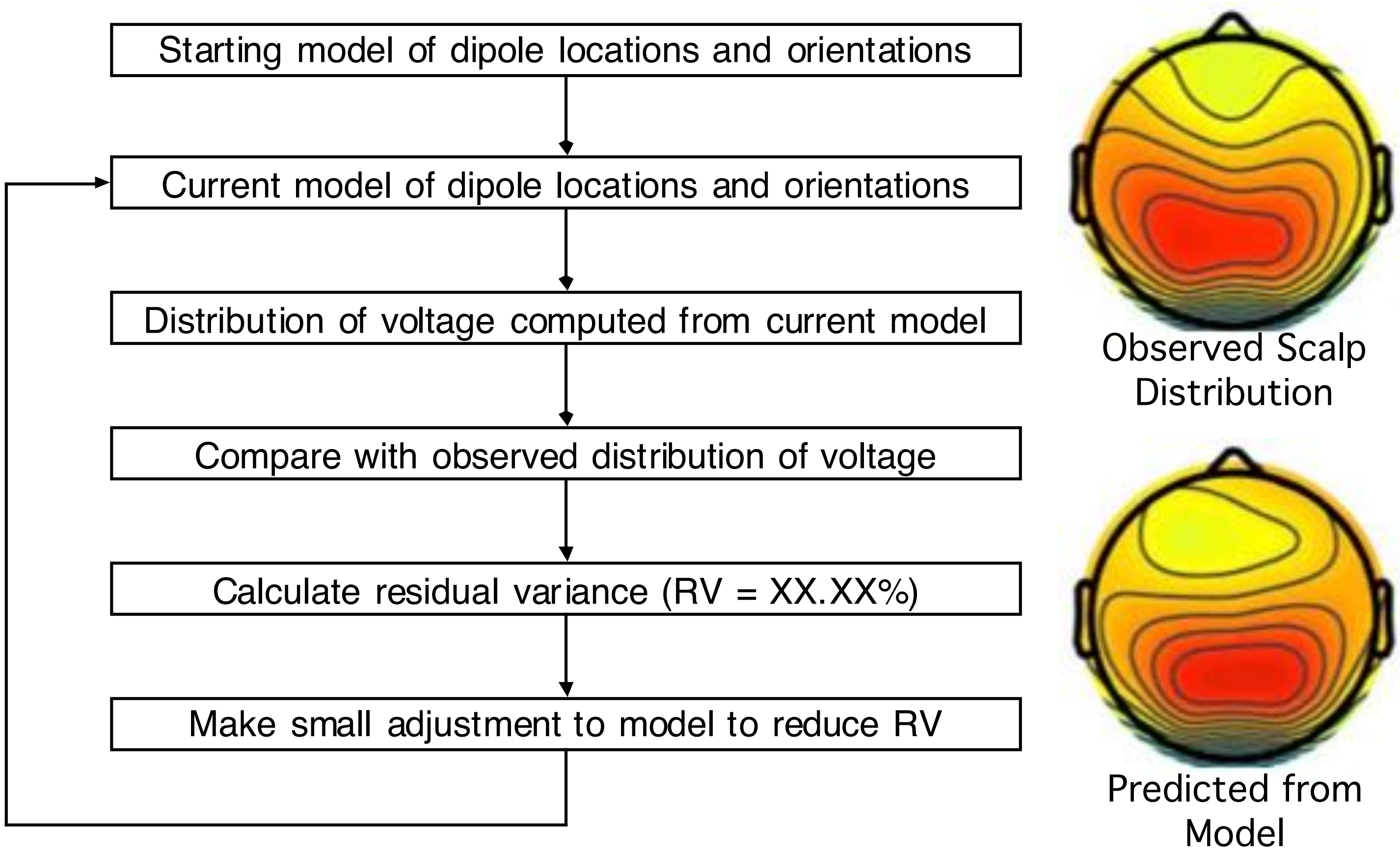
In equivalent current dipole approaches, we assume that we can account for the data reasonably well with a relatively small number of equivalent current dipoles.



Di Russo et al. (2002)

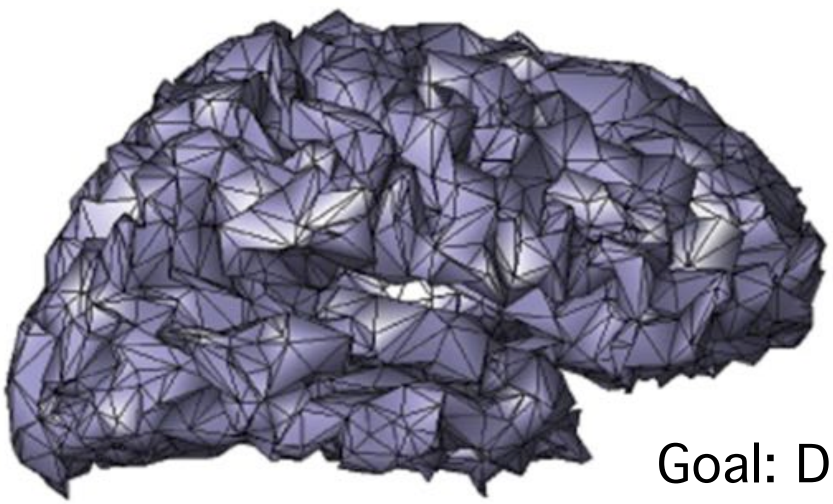
The locations and orientations of the dipoles are fixed for a given subject, but the magnitude of the signal at each dipole varies from millisecond to millisecond, giving us a source waveform.

The locations, orientations, and source waveforms are estimated by means of an iterative error minimization approach. We choose the model with the lowest residual variance (best match between predicted and observed data).

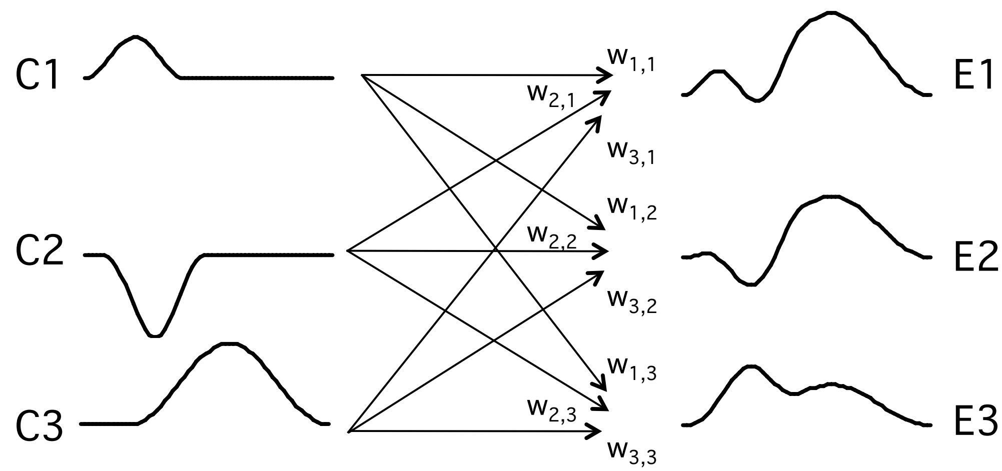


Distributed Source Approach

Using a structural MRI scan, we divide (tesselate) the cortical surface into thousands of tiny patches. We then assume that each patch is a tiny dipole. We know the locations of the patches from the structural MRI data, and we assume that the dipole for a given patch is oriented perpendicular to the cortical surface. We just need to estimate out the magnitude for each patch at each moment in time.

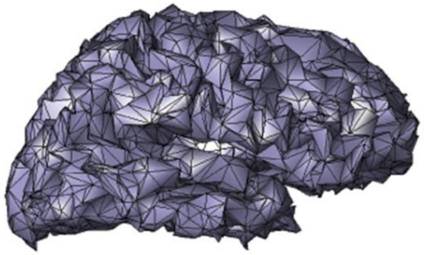


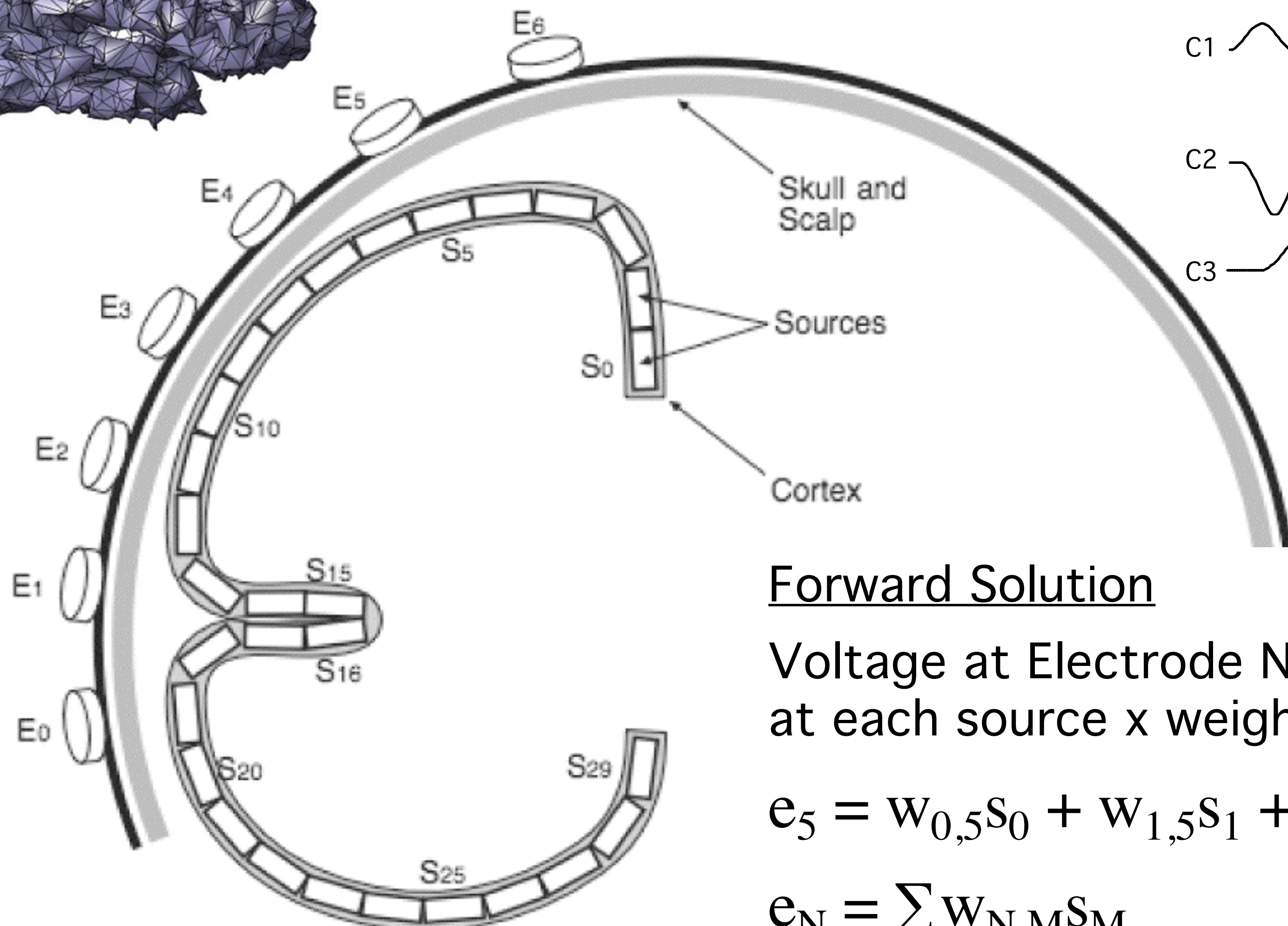
Liao et al. (2013)

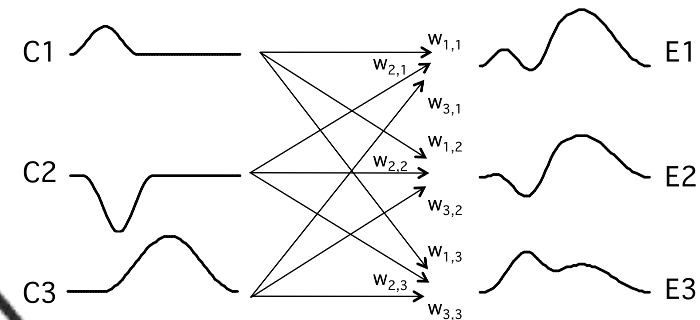


Goal: Determine magnitude of each dipole at every moment in time

Distributed Source Approach





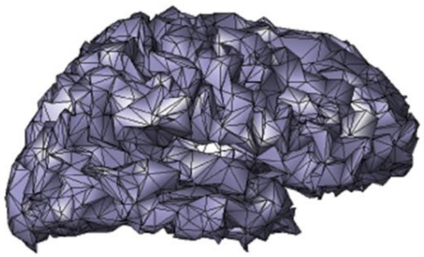


<u>Forward Solution</u>

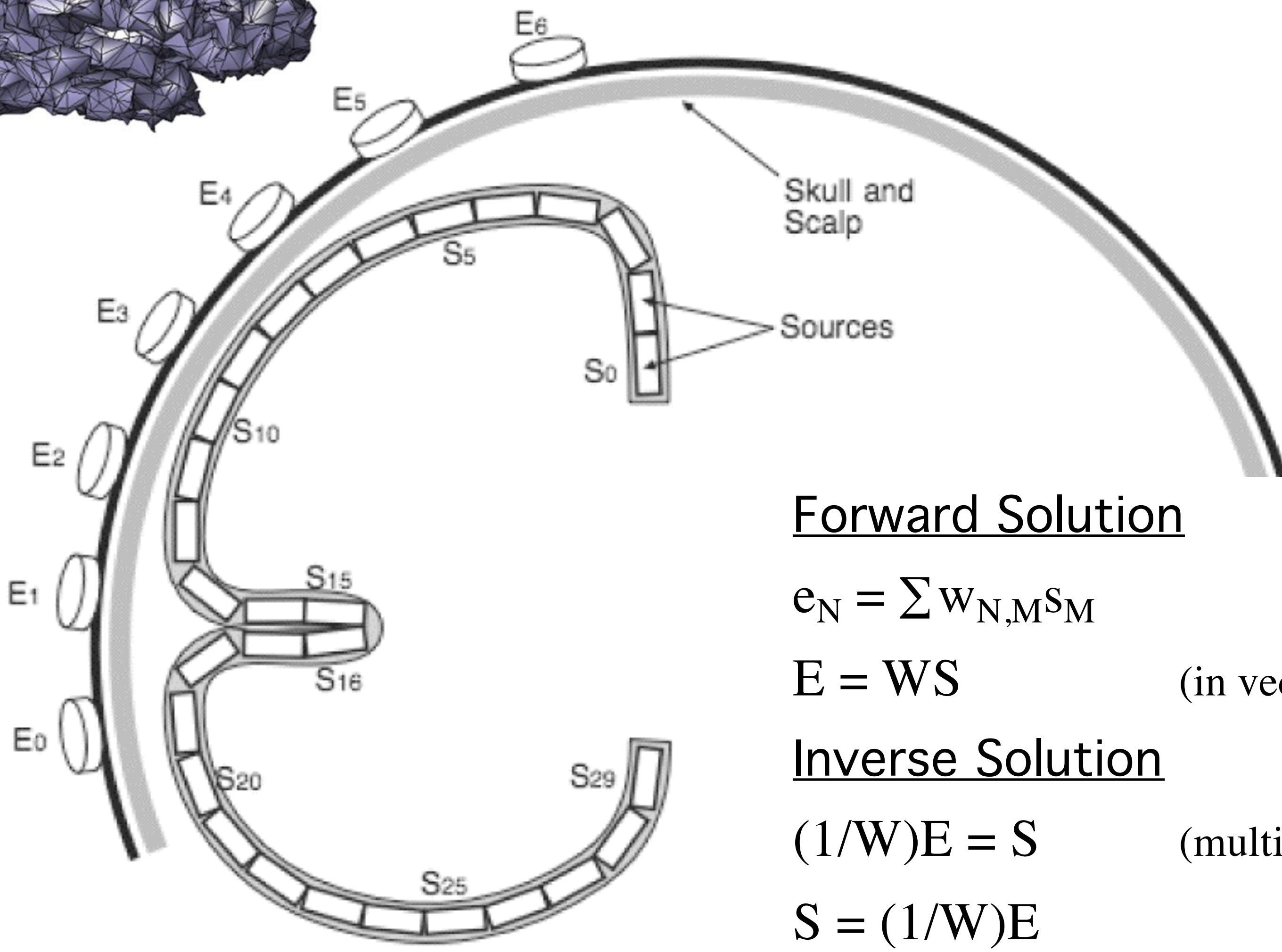
Voltage at Electrode N = Sum of voltage at each source x weight for that source

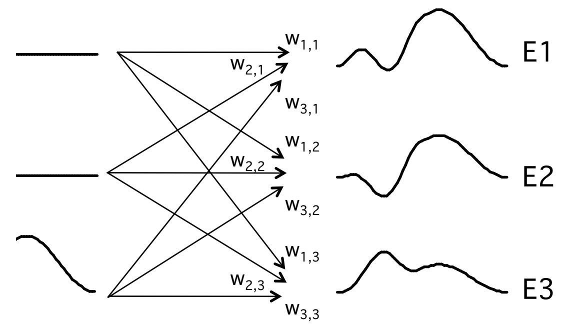
$$e_5 = w_{0,5}s_0 + w_{1,5}s_1 + w_{2,5}s_2 + \ldots$$

$$e_N = \sum w_{N,M}s_M$$



Distributed Source Approach





<u>Forward Solution</u>

$e_N = \sum w_{N,M} s_M$

$E = WS$ (in vector notation)

<u>Inverse Solution</u>

$(1/W)E = S$ (multiply both sides by 1/W)

$S = (1/W)E$

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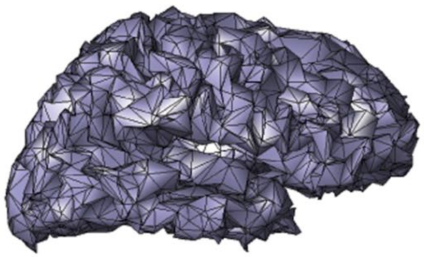
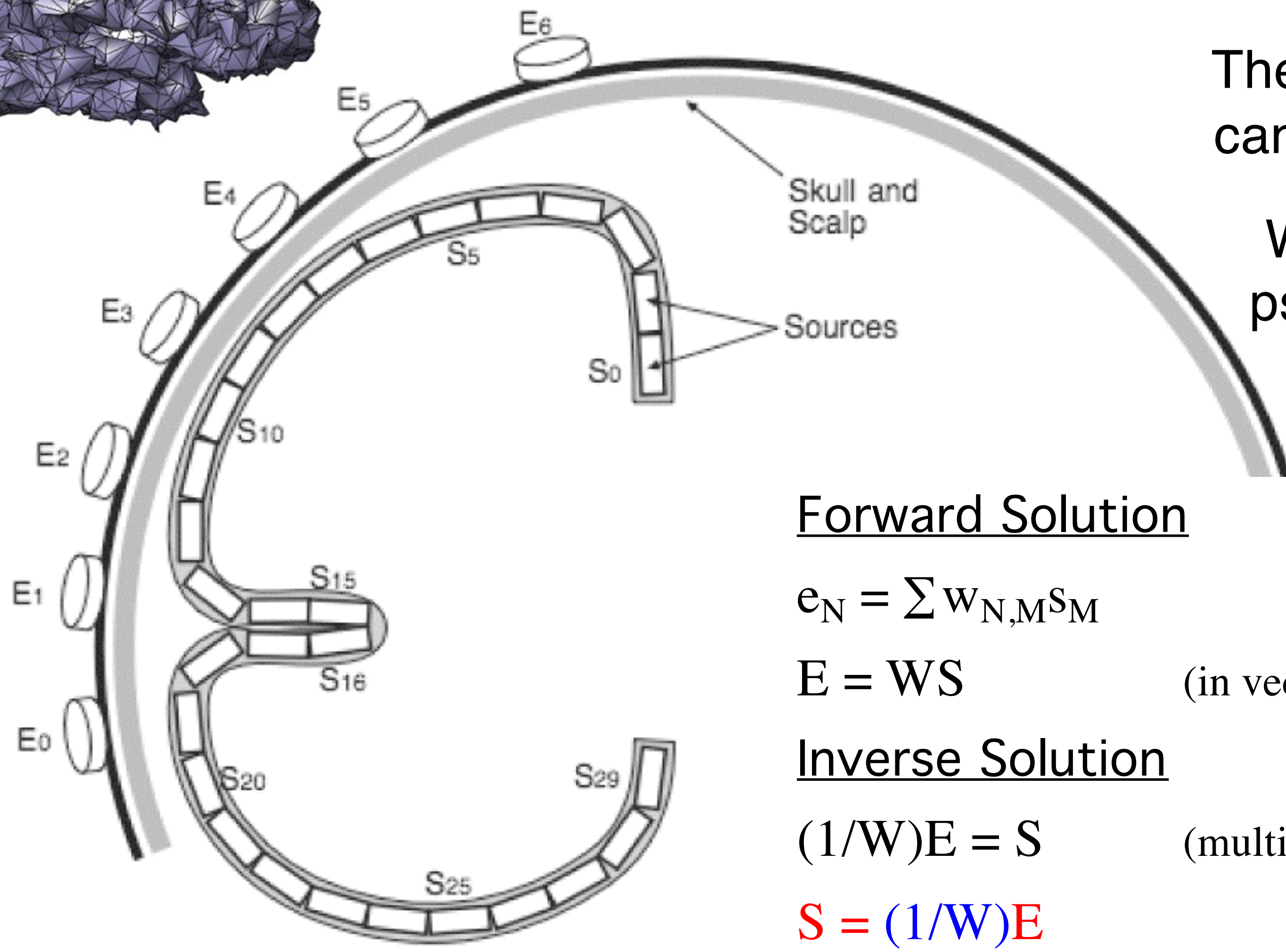
Generation & Propagation of ERPs

Challenges in ERP Source Localization



Distributed Source Approach



The matrix of weights (W) can't actually be inverted.

We have to choose a pseudo-inverse, which requires additional constraints.

<u>Forward Solution</u>

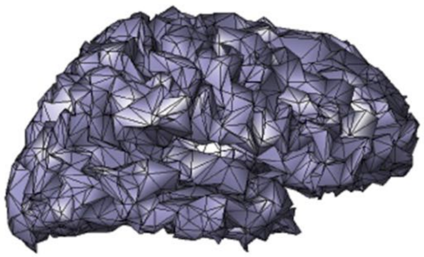
$e_N = \sum w_{N,M} s_M$

$E = WS$ (in vector notation)

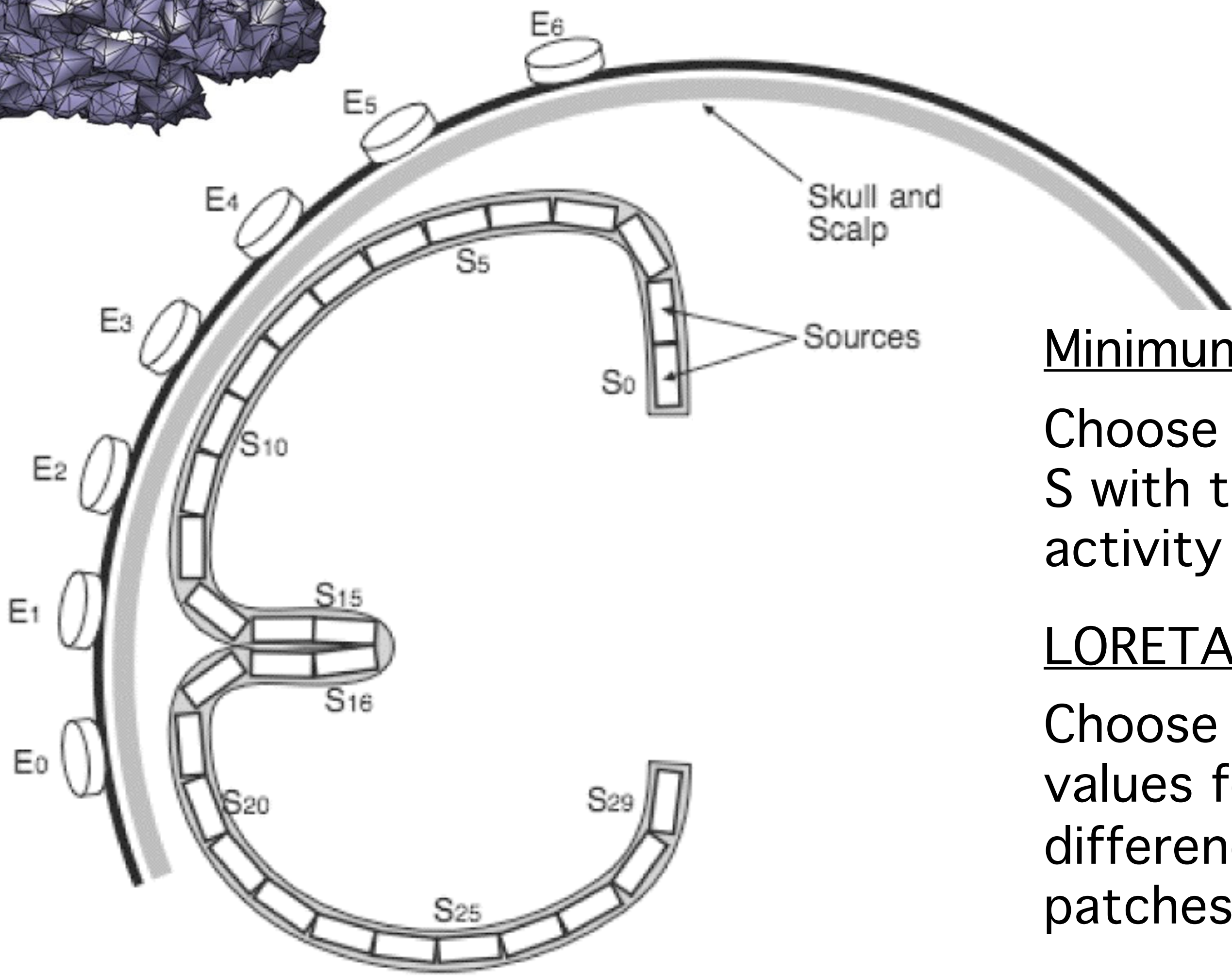
<u>Inverse Solution</u>

$(1/W)E = S$ (multiply both sides by 1/W)

$S = (1/W)E$



Distributed Source Approach

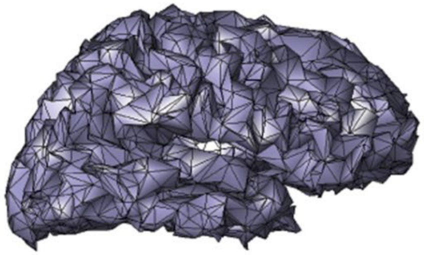


<u>Minimum Norm Solution</u>

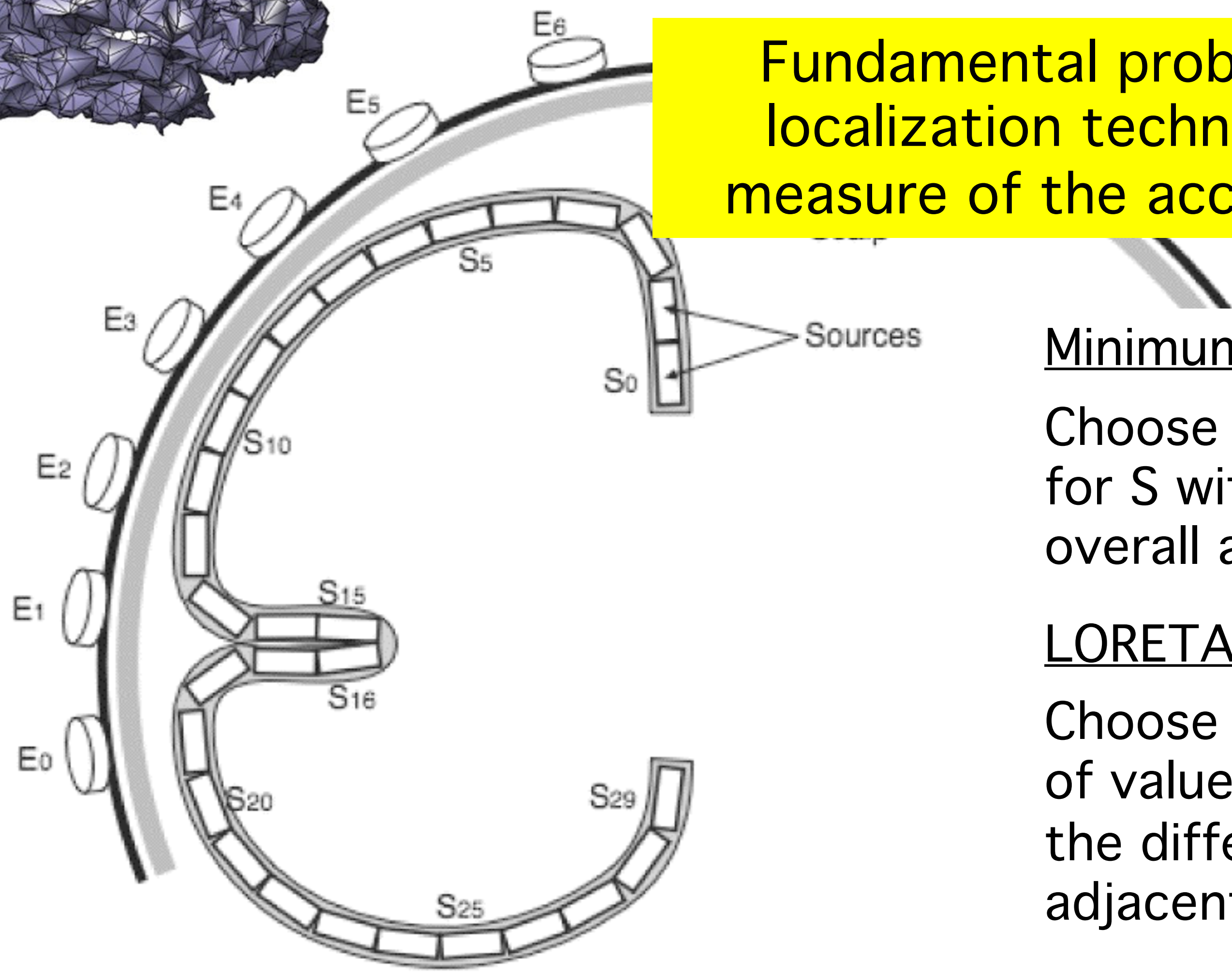
Choose the set of values for S with the smallest overall activity (the smallest "norm")

<u>LORETA Solution</u>

Choose the smoothest set of values for S (minimize the differences between adjacent patches)



Distributed Source Approach



Fundamental problem of most source localization techniques: No principled measure of the accuracy of the solution

<u>Minimum Norm Solution</u>

Choose the set of values for S with the smallest overall activity

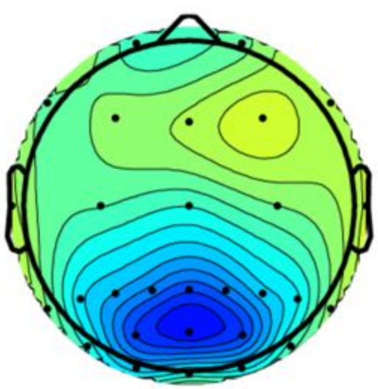
<u>LORETA Solution</u>

Choose the smoothest set of values for S (minimize the differences between adjacent patches)

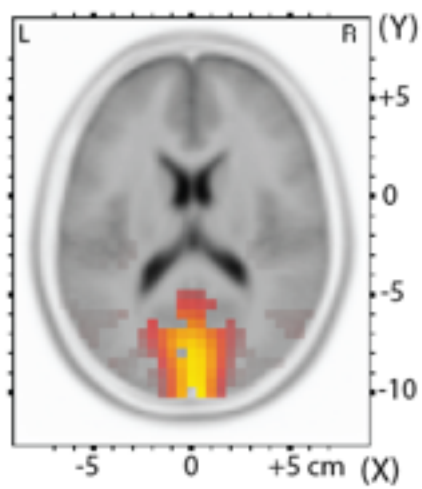
ERP source localization can be used to test the hypothesis that the data are consistent with a predicted generator location

"The present data do not provide the precision needed to distinguish between area V1 and the surrounding extrastriate areas, but these results demonstrate that the scalp distributions of the C1 wave and the C1 independence effect are at least consistent with a generator in area V1."

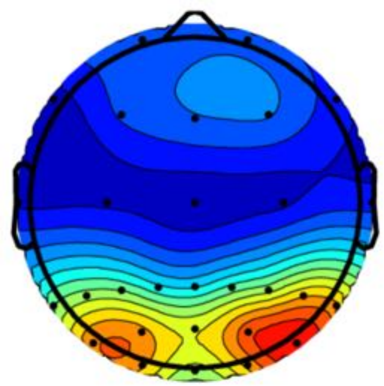
C1 Scalp Distribution



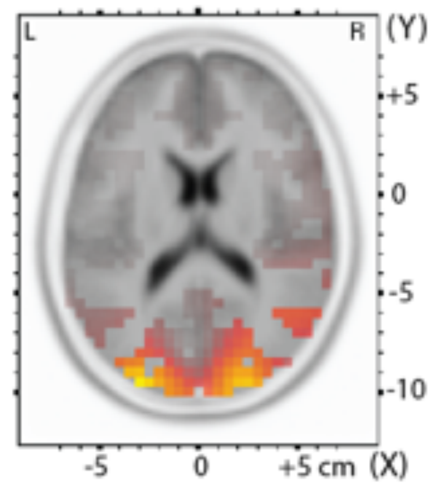
sLORETA Estimate



P1 Scalp Distribution



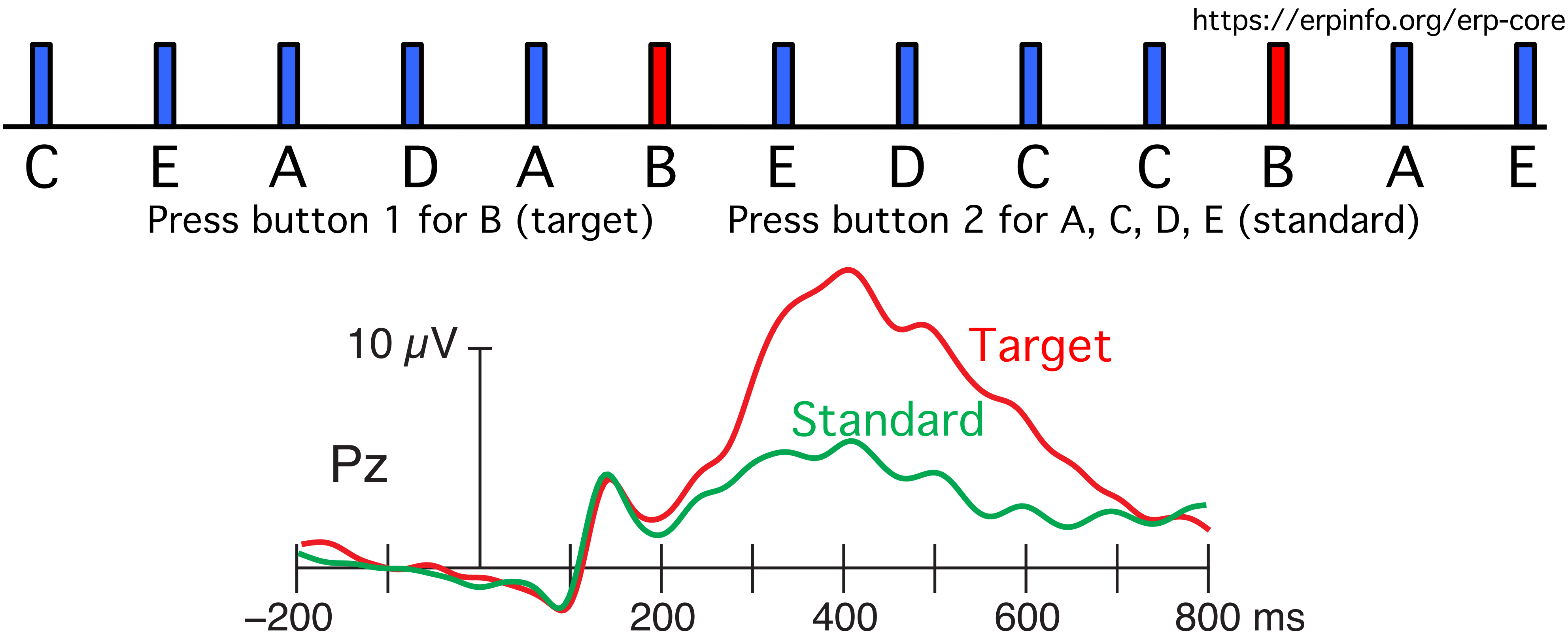
sLORETA Estimate



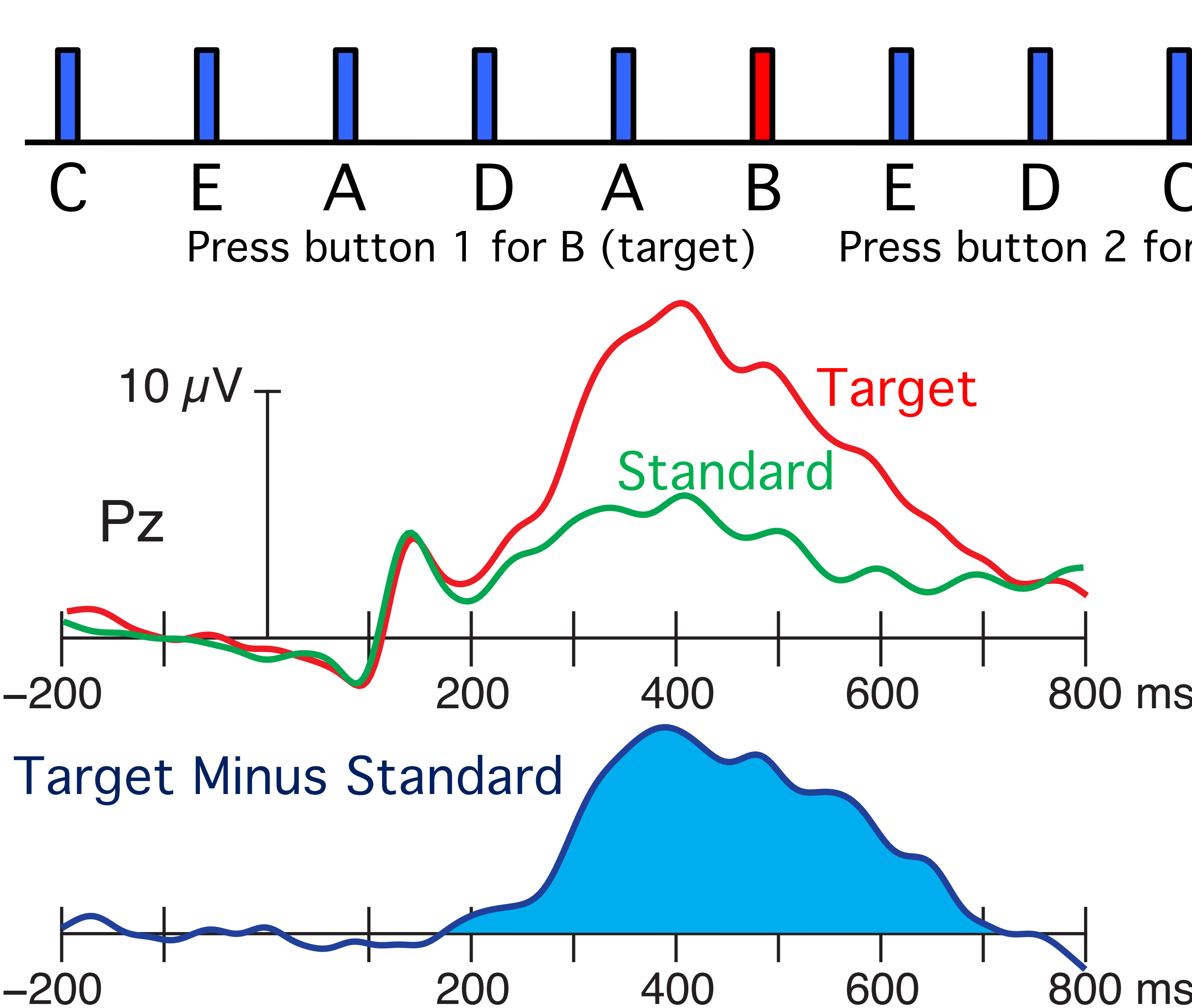
Miller, C. E., Luck, S. J., & Shapiro, K. L. (2015). Electrophysiological measurement of the effect of inter-stimulus competition on early cortical stages of human vision. Neuroimage, 105, 229–237.

Generation & Propagation of ERPs

Difference Waves

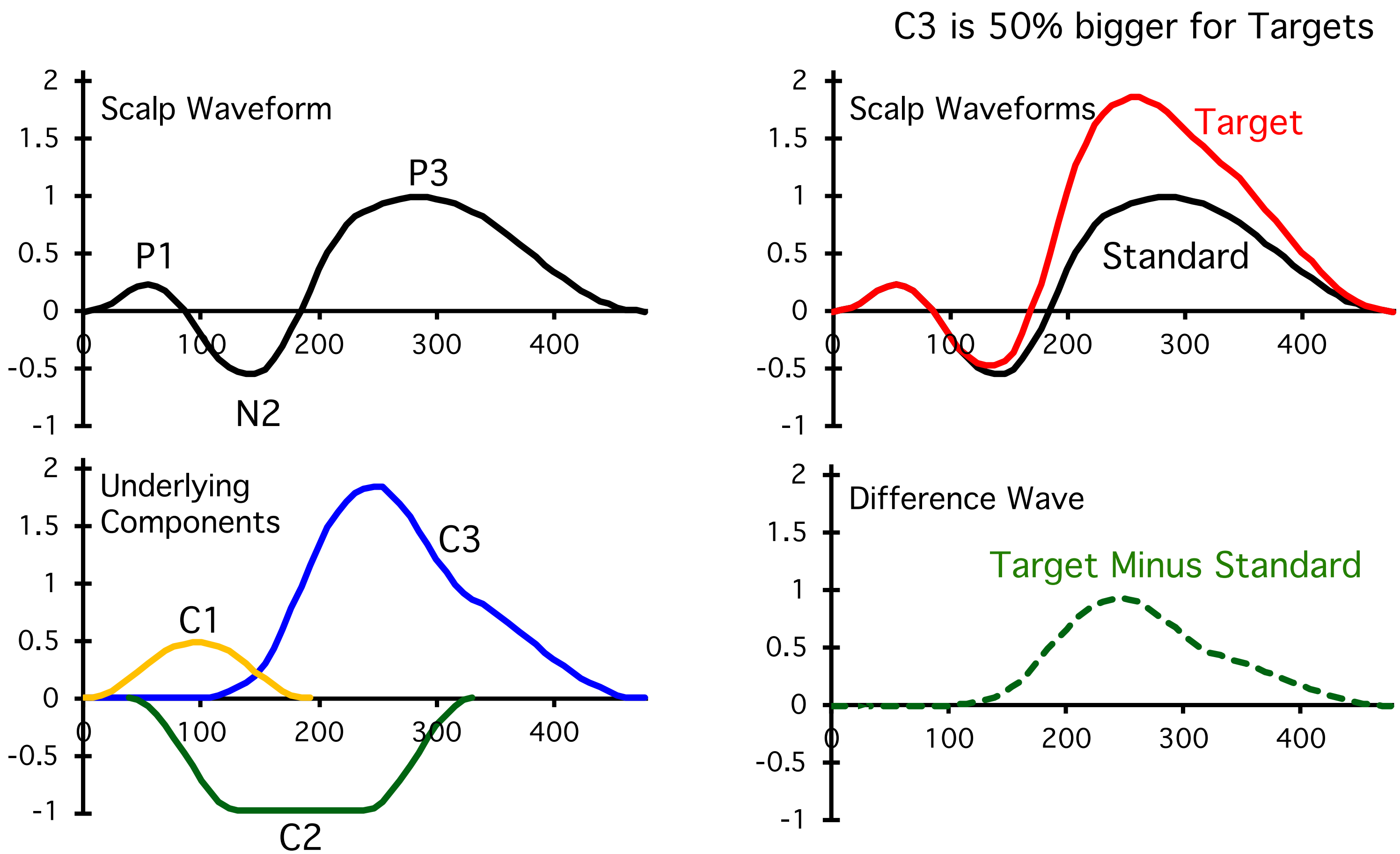


Many different ERP components sum together in these waveforms, some of which are bigger for oddballs and some of which are the same for standards and oddballs. They're all mixed together in our scalp electrodes.



The difference wave gives us the probability-sensitive activity, which will mainly be the P3 wave.

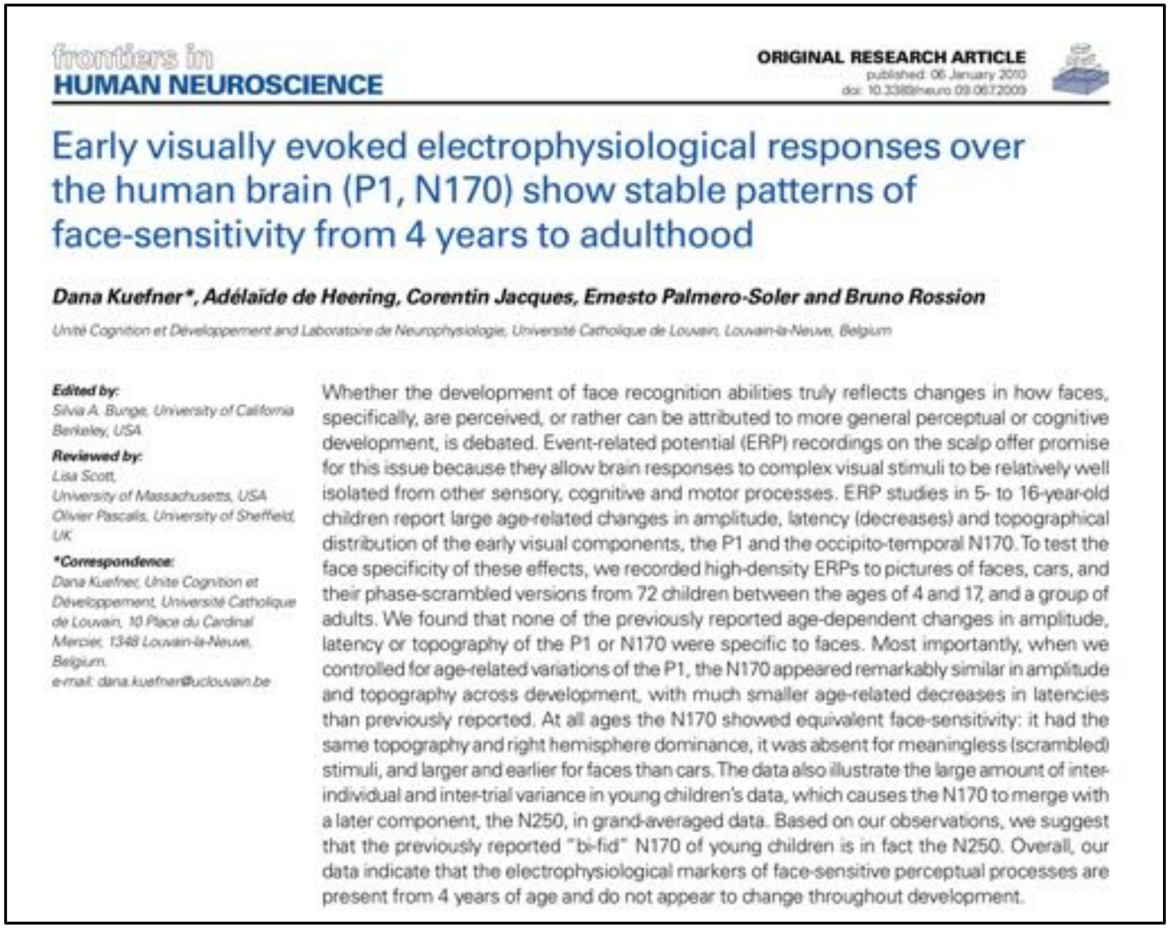
If there are other probability-sensitive components, they'll also be present in the difference wave



If we take the difference between the targets and the standards at each time point to create a rare-minus-frequent difference wave, we can recover the component that changed. The difference wave has the same shape as component C3.

Generation & Propagation of ERPs

Difference Wave Example



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HUMAN NEUROSCIENCE

ORIGINAL RESEARCH ARTICLE
published: 06 January 2010
doi: 10.3389/neuro.09.067.2009

Early visually evoked electrophysiological responses over the human brain (P1, N170) show stable patterns of face-sensitivity from 4 years to adulthood

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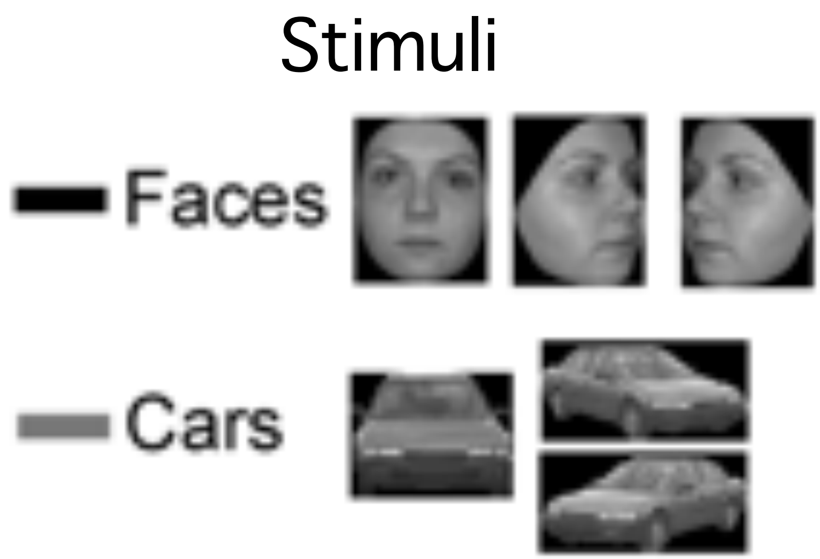
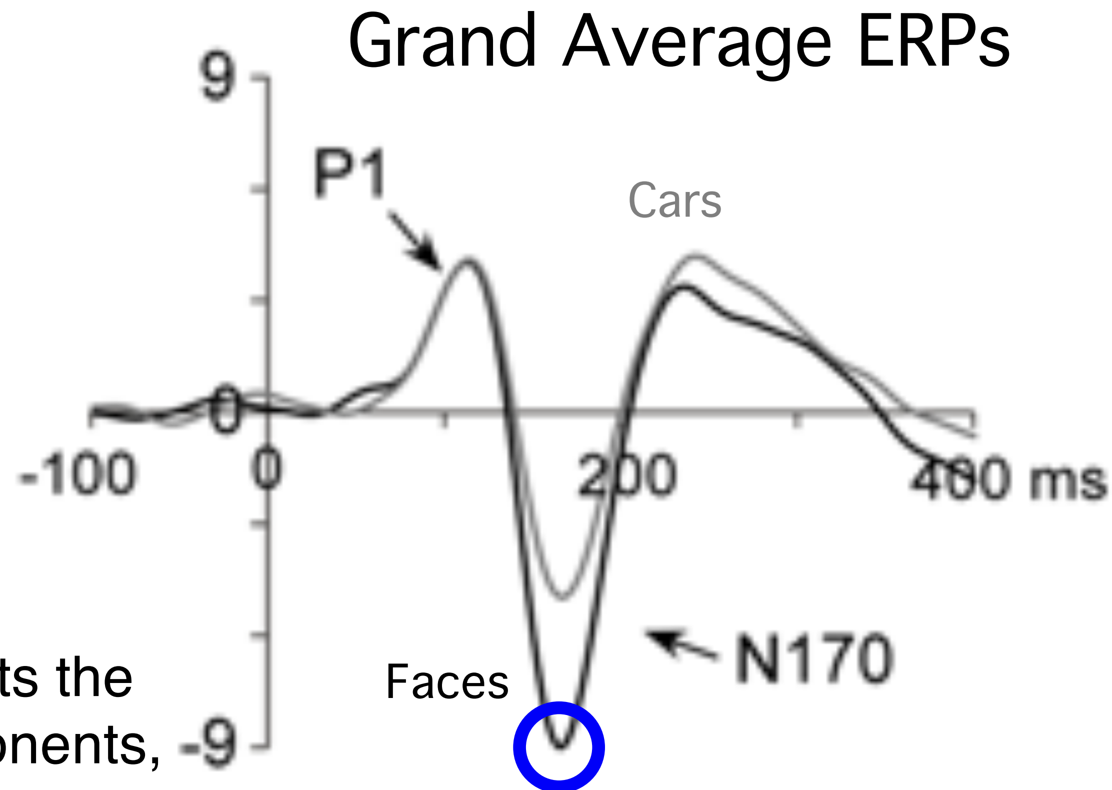
Whether the development of face recognition abilities truly reflects changes in how faces, specifically, are perceived, or rather can be attributed to more general perceptual or cognitive development, is debated. Event-related potential (ERP) recordings on the scalp offer promise for this issue because they allow brain responses to complex visual stimuli to be relatively well isolated from other sensory, cognitive and motor processes. ERP studies in 5- to 16-year-old children report large age-related changes in amplitude, latency (decreases) and topographical distribution of the early visual components, the P1 and the occipito-temporal N170. To test the face specificity of these effects, we recorded high-density ERPs to pictures of faces, cars, and their phase-scrambled versions from 72 children between the ages of 4 and 17, and a group of adults. We found that none of the previously reported age-dependent changes in amplitude, latency or topography of the P1 or N170 were specific to faces. Most importantly, when we controlled for age-related variations of the P1, the N170 appeared remarkably similar in amplitude and topography across development, with much smaller age-related decreases in latencies than previously reported. At all ages the N170 showed equivalent face-sensitivity: it had the same topography and right hemisphere dominance, it was absent for meaningless (scrambled) stimuli, and larger and earlier for faces than cars. The data also illustrate the large amount of inter-individual and inter-trial variance in young children's data, which causes the N170 to merge with a later component, the N250, in grand-averaged data. Based on our observations, we suggest that the previously reported "bi-fid" N170 of young children is in fact the N250. Overall, our data indicate that the electrophysiological markers of face-sensitive perceptual processes are present from 4 years of age and do not appear to change throughout development.

Kuefner, D., de Heering, A., Jacques, C., Palmero-Soler, E., & Rossion, B. (2010). Early Visually Evoked Electrophysiological Responses Over the Human Brain (P1, N170) Show Stable Patterns of Face-Sensitivity from 4 years to Adulthood. *Frontiers in Human Neuroscience*, *3*, 67. https://doi.org/10.3389/neuro.09.067.2009

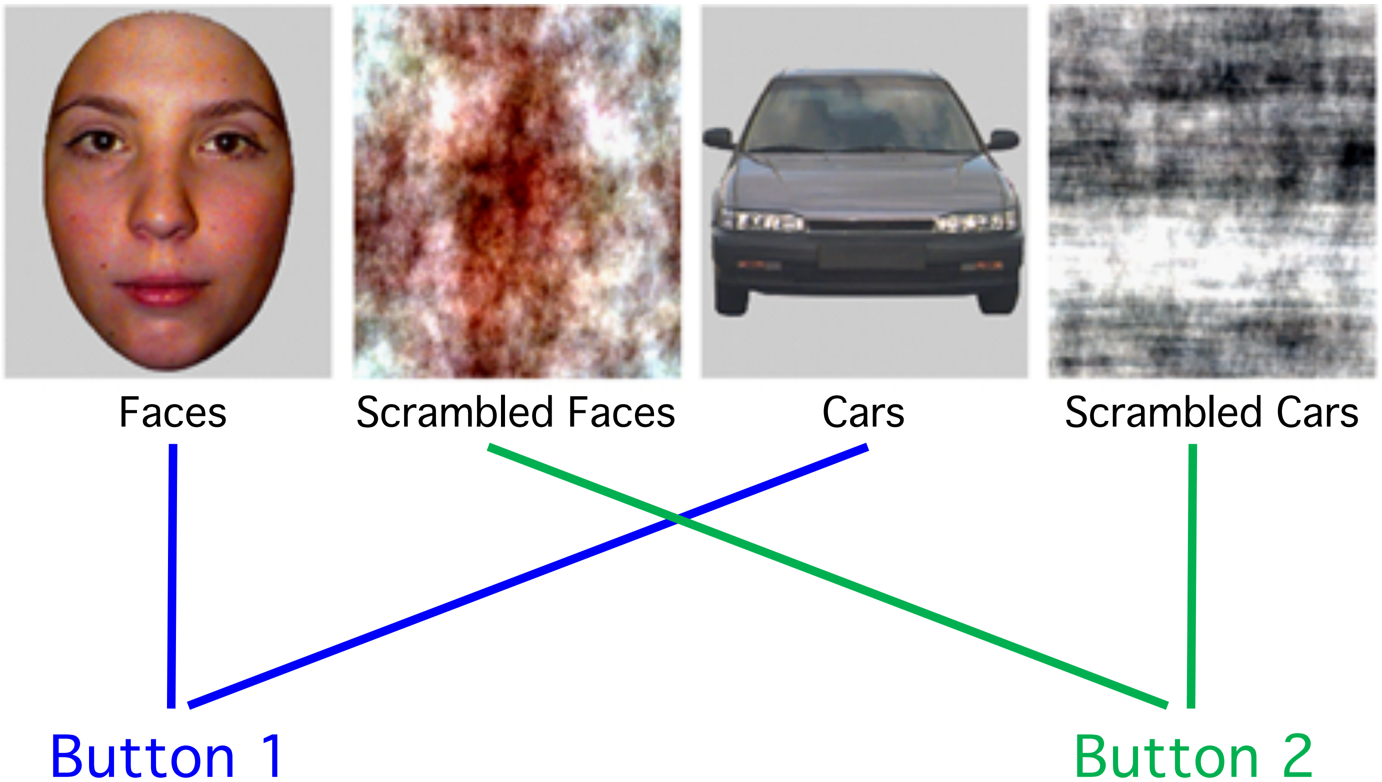
N170 and Face Processing





The overall N170 for faces reflects the sum of many different ERP components, some of which are face-specific and some of which are present for both faces and other kinds of objects.

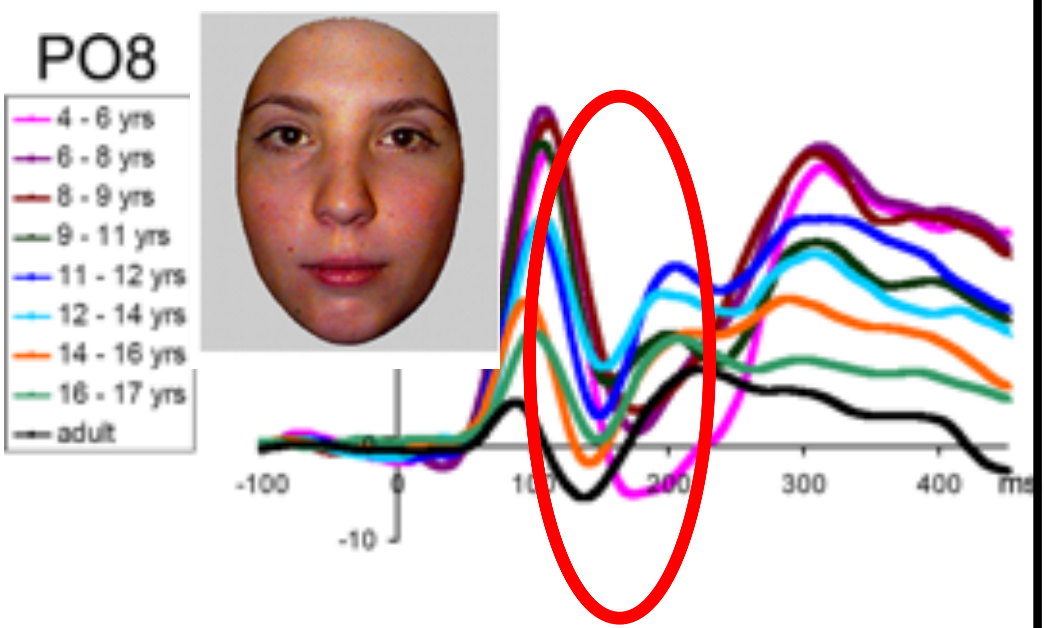
Rossion & Jacques (2012)



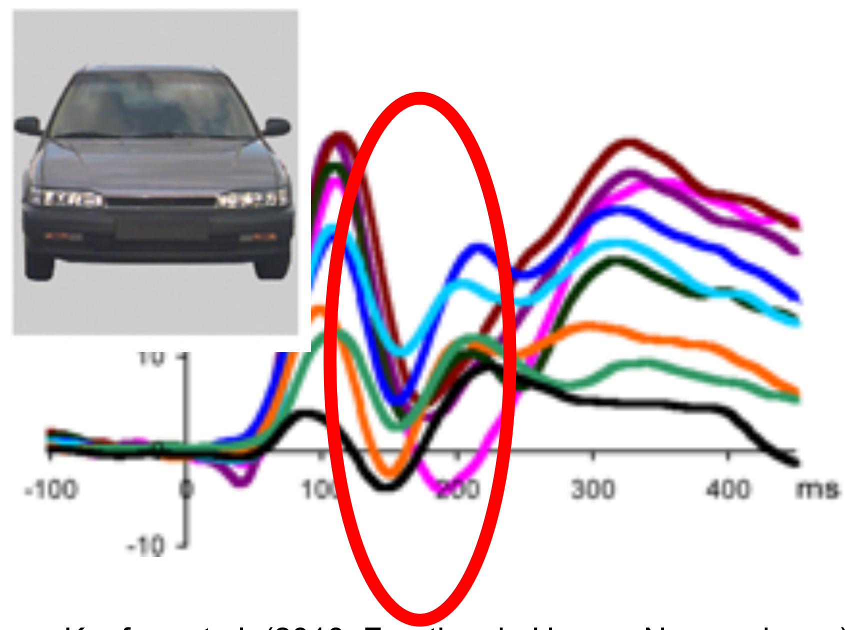
To keep the subjects alert and attentive, they had the subjects press one button for the faces and the cars and another button for the scrambled faces and the scrambled cars.

Kuefner et al. (2010, Frontiers in Human Neuroscience)

Are these huge differences in ERPs a result of changes in face processing, or do they reflect more general changes?

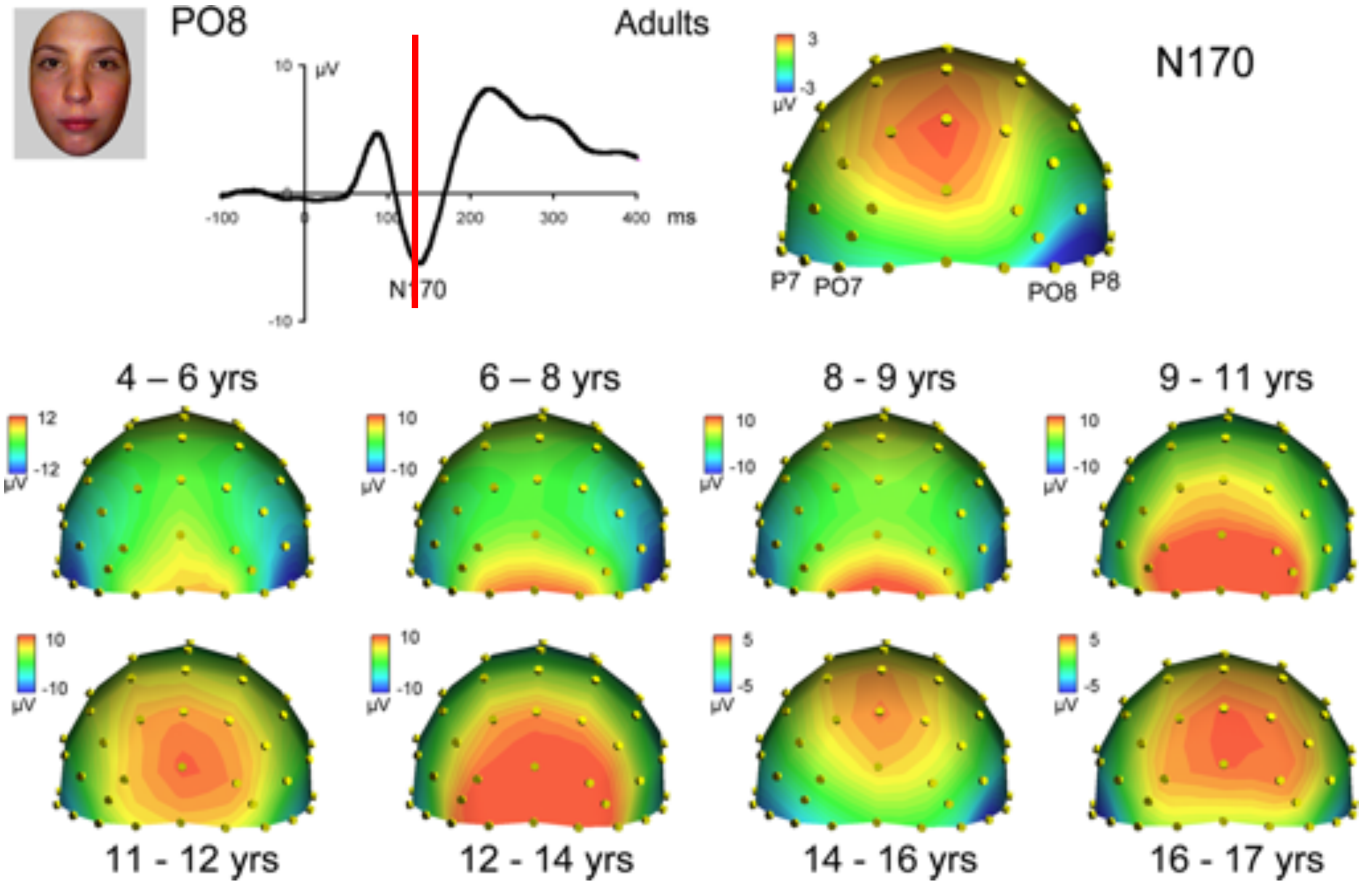


If we look at the ERPs elicited by the cars, we see the same general pattern of age-related changes. So, it seems that most of the developmental changes are not specific to faces.

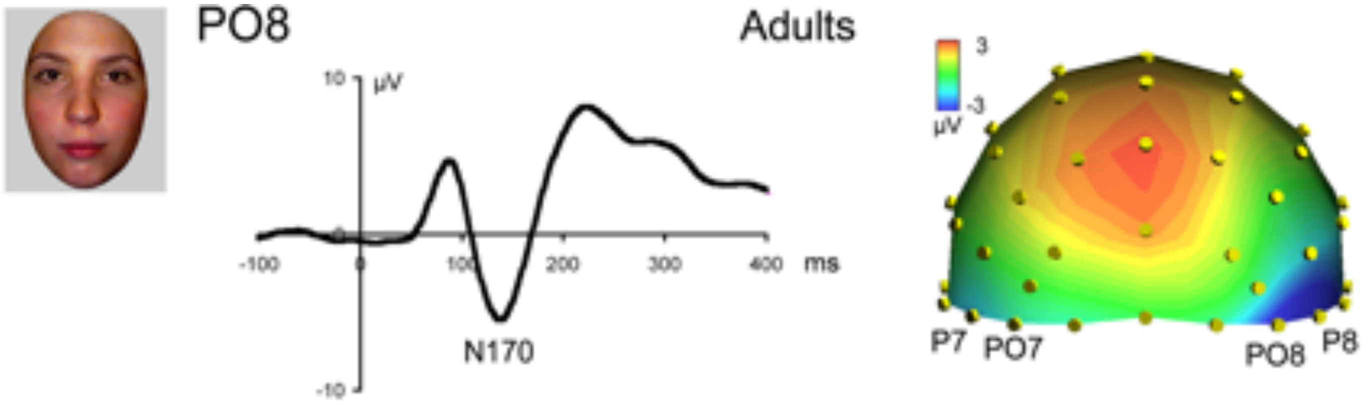


Kuefner et al. (2010, Frontiers in Human Neuroscience)

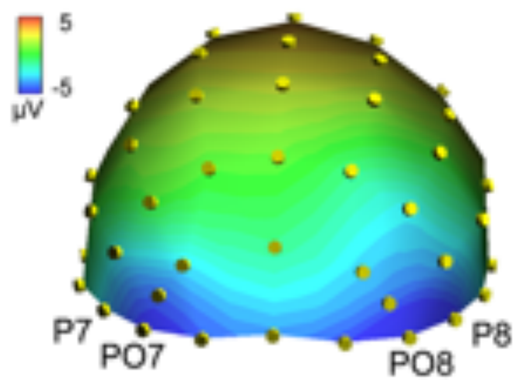
Here are the scalp distributions for the face stimuli at the time of the N170, viewed from the back of the head. Do these differences reflect changes in face processing or changes in non-specific visual processes?



Kuefner et al. (2010, Frontiers in Human Neuroscience)



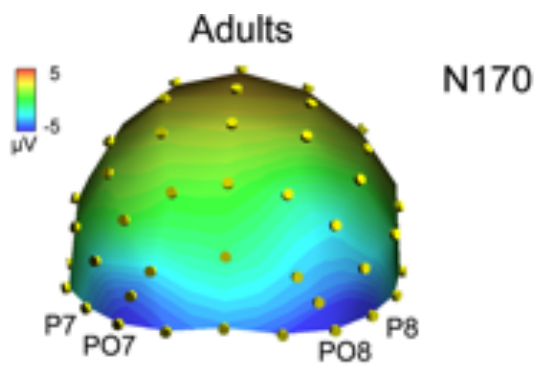
 —  = Face-Specific Activity



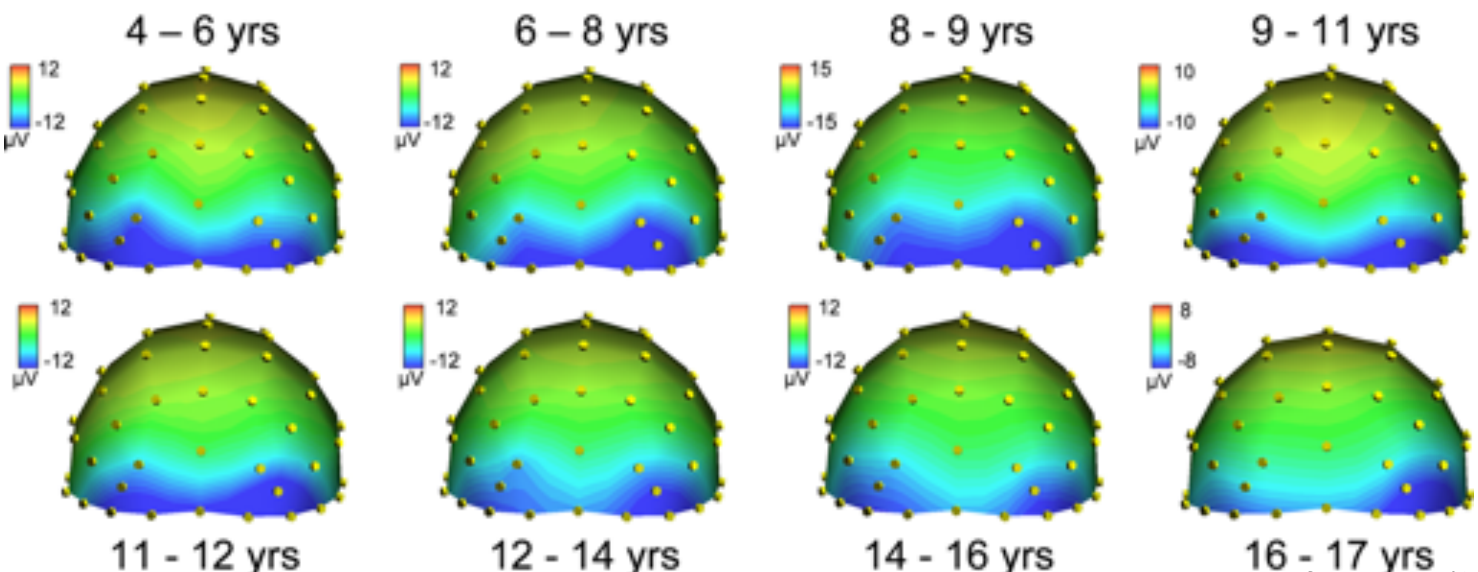
Adults

Kuefner et al. (2010, Frontiers in Human Neuroscience)

The scalp distributions of the difference waves are nearly identical across ages.



Once you isolate face-specific processing with a difference wave, you can see that the same brain regions are active for faces from 4-year-olds through adults.



Kuefner et al. (2010, Frontiers in Human Neuroscience)