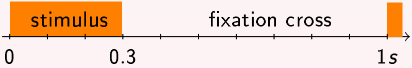
Using the Scalp Electric Field to Recognize EEG Signals

C. G. Carvalhaes, M. Perrau-Guimaraes, J. A. de Barros, P. Suppes

CSLI, Suppes Brain Lab
Stanford, CA

March 10th, 2012

EEG signals



Millisecond-range temporal resolution

Analysis techniques:

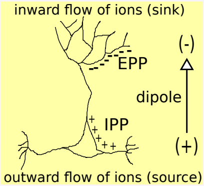
- Fourier analysis
- Coherence analysis
- Classification

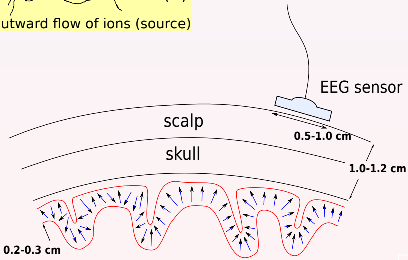
Experimental issues

- Reference electrode
- Low signal-to-noise ratio
- Poor spatial resolution

Sources of EEG

- Synaptic potentials are the most important sources of EEG.
- EEG reflects the activity of layers of cortical neurons that have similar spatial orientation.
- Pyramidal cells of the cortex are the major contributor.
- Volume conduction: outward movement of ions from the brain sources.





The scalp electric field is tangential

The electric field, $\mathbf{E}$ $(\mu\mathrm{V}/\mathrm{mm})$, is related to the current density, $\mathbf{J}$ $(\mu\mathrm{A}/\mathrm{mm}^2)$:

$$\mathbf{J}(\mathbf{r},t) = \sigma\mathbf{E}(\mathbf{r},t),$$

where σ (S/mm) is the electrical conductivity. We assume that

$$\mathbf{J}_{\mathrm{tan}} = \sigma_{\mathrm{tan}}\mathbf{E}_{\mathrm{tan}} \quad \text{and} \quad J_{\mathrm{radial}} = \sigma_{\mathrm{radial}} E_{\mathrm{radial}}.$$

Since $\sigma_{\mathrm{air}} \approx 0$, the electric field is tangential on the outer scalp surface:

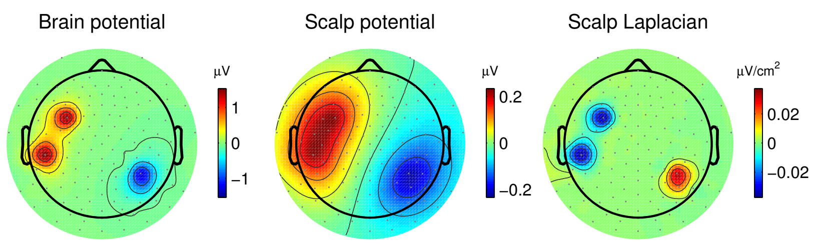
$$\mathbf{E}^{\mathrm{scalp}}(\mathbf{r},t) = \cancel{E_r(\mathbf{r},t)}\hat{\mathbf{r}} + E_\theta(\mathbf{r},t)\hat{\theta} + E_\varphi(\mathbf{r},t)\hat{\varphi}.$$

Therefore,

$$\mathbf{E}^{\mathrm{scalp}}(\mathbf{r},t) = -\vec{\nabla}_{\mathrm{surf}} V(\mathbf{r},t).$$

The divergence of E

$$\vec{\nabla}_{\text{surf}} \cdot \mathbf{E} = -\vec{\nabla}_{\text{surf}} \cdot \vec{\nabla}_{\text{surf}} V = -\nabla^2_{\text{surf}} V.$$



Distributions due to three radial dipoles located 6.2 cm from the center of the head. (θ, φ)-coordinates are: $(75°, 230°)$, $(65°, 55°)$, and $(80°, 100°)$. Brain, skull, and scalp were represented as concentric spheres of radii 8.0, 8.6, and 9.2 cm, respectively. The brain and scalp had the same resistivity of $300\,\Omega\cdot\text{cm}$ and the skull was 80 times more resistive.

(*) Carvalhaes & Suppes, Neural Computation (2011)

Exp. I: Thirty-two CV syllables (128 channels)

pi	ti	bi	gi	fi	si	vi	zi
pæ	tæ	bæ	gæ	fæ	sæ	væ	zæ
pu	tu	bu	gu	fu	su	vu	zu
pa	ta	ba	ga	fa	sa	va	za

The vowels are like in: **meet, cat, soon, spa.**

Highest recognition rates (%) — Consonant (red), Syllable (blue), Vowel (black)

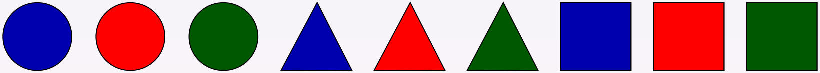
	Potential			Laplacian			Electric Field			Laplacian/Elec. Field (LEF)		
S1	44.0	12.2	36.4	57.0	19.8	**45.8**	58.0	17.6	37.8	**66.0**	**22.6**	43.1
S2	40.8	9.2	33.9	34.9	8.7	36.7	**40.5**	**9.4**	37.2	39.1	9.1	**37.8**
S3	31.2	7.9	35.8	32.8	8.3	35.8	36.0	8.4	**37.7**	**37.7**	**9.0**	37.3
S4	30.3	6.8	34.2	27.1	6.1	**38.7**	**30.6**	6.8	38.2	30.1	**7.5**	**38.7**
Avg.	36.9	9.3	35.3	40.0	11.7	**39.9**	42.9	11.3	37.7	**45.7**	**13.2**	39.6

S1 - 7169 trials; S2 - 3589 trials; S3 - 6273 trials; S4 - 4481 trials.

Chance level: 12.5%; 3.1%; 25.0%.

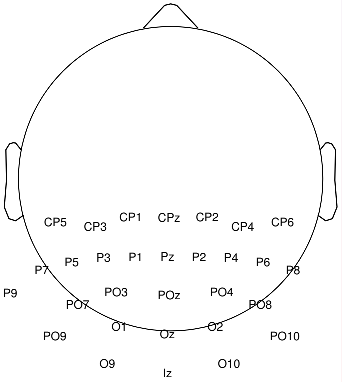
(*) Rui Wang, PhD. Dissertation (2011)

Exp. II: Nine color-shape images (32 channels)



Recognition rates (%)		2700 trials		
	Poten.	Laplac.	EF	LEF
S1	57.3	82.1	82.5	**87.5**
S2	42.2	50.8	66.5	**68.9**
S3	35.7	59.1	61.3	**70.0**
S4	50.3	63.4	67.0	**73.3**
S5	59.1	71.8	76.6	**81.8**
S6	53.9	58.1	66.2	**71.1**
S7	55.0	55.9	66.4	**72.2**
Avg.	50.5	63.0	69.5	**75.0**

Chance level: 11.1%.



Exp. III: Seventy-two face and non-face images (128 channels)

72 images
6 categories:

- human face
- human body
- animal face
- animal body
- natural object
- artificial object

Recognition rates (%) Image (red) Category (blue) 5186 trials

	Potential		Laplacian		Elec. Field		LEF	
S1	10.5	45.5	12.4	46.6	21.1	56.1	**26.3**	**59.9**
S2	8.2	49.7	11.0	53.5	14.5	59.4	**21.4**	**65.7**
S3	12.6	55.1	15.5	56.0	17.7	57.5	**24.2**	**64.5**
S4	6.9	44.1	10.1	49.5	8.9	53.5	**12.7**	**58.9**
S5	15.5	52.2	17.2	60.5	24.3	68.0	**38.5**	**76.4**
S6	15.0	56.3	19.4	60.3	32.7	70.5	**42.7**	**78.8**
S7	11.6	59.0	14.0	60.7	17.4	65.3	**25.7**	**72.8**
S8	6.6	40.2	7.6	42.4	8.6	48.4	**10.5**	**54.6**
S9	7.8	50.0	7.9	49.5	11.1	53.4	**14.9**	**57.2**
S10	14.7	63.4	19.9	70.6	30.4	76.0	**44.4**	**82.0**
Avg.	10.9	51.6	13.5	55.0	18.7	60.8	**26.1**	**67.1**

Chance level: 1.4%; 16.7%.

(*) Blair Kaneshiro, in preparation (2012)

Exp. IV: Two-class mental task (64 channels)

Highest recognition rates (%)					600 trials
	Potential	Laplacian	Elec. Field	LEF	LEF+PCA
S1	74.4	**91.7**	90.1	90.9	**93.4**
S2	70.2	**75.2**	72.7	71.9	**80.2**
S3	74.4	**79.3**	**79.3**	**79.3**	**83.5**
S4	72.5	78.3	**82.5**	81.7	**88.3**
S5	78.5	**93.4**	82.6	83.5	90.9
S6	57.5	**75.0**	70.8	68.3	72.5
S7	80.2	**85.1**	**85.1**	76.0	**89.3**
S8	76.9	81.0	**83.5**	82.6	**90.9**
S9	**76.0**	74.4	**76.0**	74.4	**76.0**
S10	82.6	82.6	**84.3**	76.0	**90.9**
S11	75.2	**76.9**	75.2	72.7	**85.1**
Avg.	74.3	**81.4**	81.1	77.6	**85.5**

Chance level: 50%.

Conclusions & Remarks

- The electric field was effective to reduce error in the recognition of phonemes, images, and mental states.
- The method is reference-free and worked for different electrode systems.
- Combination with PCA resulted in further improvement.
- The method is computationally efficient, involving only a linear transformation of the input signal.
- Estimates of the electric field can be improved by: (*i*) using a more realistic model of the head; (*ii*) determining the precise location of the electrodes; (*iii*) increasing the electrode density.