Theory and Application of Electrocorticographic (ECoG) Signals in Humans

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Berlin, Germany
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Electrocorticographic Signals (ECoG) in Humans

- Characteristics
- Relationship
- ECoG
- BCI Control
- Diagnosis
- Open Questions
- Future Directions

Donnerstag, 16. Juli 2009
SIGNAL ACQUISITION AND PROCESSING → SIGNAL FEATURES → TRANSLATION ALGORITHM → DEVICE COMMANDS
## Different BCI Signal Modalities

<table>
<thead>
<tr>
<th>Regional Domain</th>
<th>Signals</th>
<th>Invasiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEG</td>
<td>3-5cm</td>
<td>Non-invasive</td>
</tr>
<tr>
<td>ECoG</td>
<td>.5-1cm</td>
<td>Invasive</td>
</tr>
<tr>
<td>Field Potential</td>
<td>1mm</td>
<td></td>
</tr>
<tr>
<td>Single Unit</td>
<td>200 microns</td>
<td></td>
</tr>
</tbody>
</table>

Leuthardt, Schalk et al., *Neurosurgery*, 2006
Electrocorticography (ECoG)
Electrocorticographic Signals (ECoG) in Humans

Brunner, Ritaccio, Schalk et al., Epilepsy and Behavior, 2009
We find in baboons that such chronically implanted electrodes (of diameter $\frac{1}{2} - 1$ mm) record activity in the spike frequency range (1000-10000 Hz) that accompanies and just precedes specific voluntary movements of the contralateral arm or leg. ... The ratio of signal to noise can be greatly improved by selecting lower frequencies ... [between] 80 and 250 Hz.

Brindley and Craggs, *J. Physiol. (Lond.)*, 1972
We are interested in the possibility of using signals from the motor cortex for driving an artificial motor pathway, a powered limb or a powered splint in paraplegic, hemiplegic or tetraplegic patients. For this purpose it is safest to place the recording electrodes inside the skull but outside the dura mater.

Brindley and Craggs, *J. Physiol. (Lond.*), 1972
Movement control requires recordings from neurons.

J.K. Chapin, Current Opinion in Neurology, 2000

It is impossible ... to obtain a direct readout of movement intent [without action potentials].

J.P. Donoghue, Nature Neuroscience, 2002
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More Recently ...
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Pesaran et al., *Nature Neuroscience, 2002*

“Local field potential activity discriminated between directions with approximately the same accuracy as the spike rate.”
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“Hand movement target and velocity can be inferred from multiple local field potentials (LFPs) in single trials approximately as efficiently as from multiple single-unit activity (SUA) recorded from the same electrodes.”
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“The fidelity of the decoding [of hand position], reported in the present study [using ECoG in humans], is within the range of those achieved using implanted microelectrodes in monkeys.”
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“[Hand] movement directions could be inferred on a single-trial basis from MEG activity. ... Based on simultaneous MEG and EEG recordings, we show that the inference of movement direction works equally well for both recording techniques.”
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Electrocorticographic Signals (ECoG) in Humans

- **BCI Control**
- **Relationship**
- **Diagnosis**
- **Open Questions**
- **Future Directions**
- **Characteristics**
  - mu/beta rhythms
  - gamma activity
  - local motor potential
- **ECoG**

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e.g., Crone et al., 1998, 2000, 2001; Graimann et al., 2002; Fetz, Ojemann et al., 1999, 2001; Sinai et al., 2005; Miller, Schalk et al., 2007; Leuthardt, Schalk, et al., 2007; Brunner, Schalk et al., 2009
Mu/Beta and Gamma

Miller, Schalk et al., in preparation

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Mu/Beta and Gamma

Miller, Schalk et al., in preparation

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Mu/Beta and Gamma

Miller, Schalk et al., in preparation

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The Local Motor Potential (LMP)

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Electrocorticographic Signals (ECoG) in Humans

- ECoG
- Characteristics
- General movements
- Other types of sensors
- Specific movements
- Diagnosis
- Open Questions
- Future Directions
- BCI Control
- Relationship
Relationship with General Movement Parameters:
Motor Homunculus
Relationship of ECoG with Hand/Tongue Movements
Relationship of Gamma With Speech Function

Kim, Schalk, J Neurosci, in submission; Pei, Schalk, in preparation

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Relationship of Gamma With Speech Function

Leuthardt, Schalk et al., in preparation
Relationship of Gamma With Electrical Stimulation

Crone et al., Brain, 1998; Sinai et al., Brain, 2005; Miller, Schalk et al., J Neurosci, 2007; Leuthardt, Schalk et al., Neurosurgery, 2007; Towle et al., Brain, 2008; Brunner, Schalk et al., Epilepsy and Behav, 2009
Relationship of ECoG with Multi-Unit Activity (in rats)

Kasanetz et al., *J Physiol*, 2006
Relationship of Gamma with fMRI

*Fluctuations in hemodynamic response were only loosely related to action potential frequency but tightly correlated to the power of LFP oscillations in the gamma range.*

Niessing et al., *Science*, 2005

*Gamma band modulations co-localize with BOLD variations*

Lachaux et al., *Hum Brain Mapp*, 2007
Relationship of ECoG with Details of Movements: Decoding of Function

**INPUT**
- ECoG signal samples: $s_n(k)$
- Kinematic parameters: $c(n)$

**SIGNAL PRE-PROCESSING**
- Signal Interpolation: $s_n(k) \rightarrow s'_n(k)$
- Spatial Filtering: $s'_n(k) \rightarrow s''_n(k)$

**FEATURE EXTRACTION**
- Spectral Estimation: $s''_n(k) \rightarrow a_j(n)$

**FEATURE PROCESSING**
- Smoothing
- Whitening
- Optimal Filtering
- Transformation

**FEATURE SELECTION**
- Automatic

**DECODING**
- Linear
- Non-linear

**PERFORMANCE EVALUATION**

$$r_i = \frac{\sum c_i^*c_j} {\sqrt{\left[\sum c_i^2 - (\sum c_i)^2\right] \left[\sum c_j^2 - (\sum c_j)^2\right]}}$$
Decoding Direction of Hand Movements
Tuning to Direction of Hand Movements

Schalk et al., *J Neural Eng*, 2007

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Tuning to Direction of Hand Movements

Schalk et al., *J Neural Eng*, 2007
Spatio-Temporal Gamma Activity Related to Hand Movements

Schalk et al., *J Neural Eng*, 2007
Spatio-Temporal Gamma Activity Related to Hand Movements

Schalk et al., *J Neural Eng*, 2007
Decoding Hand Position

Schalk et al., *J Neural Eng*, 2007

Pistohl et al., *J Neurosci Meth*, 2008
Decoding Hand Movements

<table>
<thead>
<tr>
<th>Study and Source</th>
<th>Position $r$</th>
<th>Velocity $r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwartz and Moran, 1999, p. 2713</td>
<td>–</td>
<td>0.77</td>
</tr>
<tr>
<td>Carmena et al., 2003, Fig. 1F &amp; 3C</td>
<td>0.33-0.63</td>
<td>0.27-0.73</td>
</tr>
<tr>
<td>Paninski et al., 2004, Table 1</td>
<td>0.47</td>
<td>–</td>
</tr>
<tr>
<td>Lebedev et al., 2005, Table 2</td>
<td>–</td>
<td>0.56</td>
</tr>
<tr>
<td>Averbeck et al., 2005, est. from Fig. 8A,B</td>
<td>–</td>
<td>0.74</td>
</tr>
<tr>
<td>Schalk et al., 2007</td>
<td>0.52</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Schalk et al., J Neural Eng, 2007
Response to Thumb Movement
Response to Index Finger Movement
Classification of Individual Fingers in 5 Subjects

Kubanek, Schalk et al., *J Neural Eng*, in revision
Decoding Thumb Flexion

\[ r = 0.80 \]
\[ r = 0.74 \]
\[ r = 0.66 \]
\[ r = 0.37 \]
\[ r = 0.52 \]

A
B
C
D
E

--- ACTUAL
----- DECODED

3 s

Kubanek, Schalk et al., *J Neural Eng*, in revision

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Decoding Thumb Flexion

Kubanek, Schalk et al., *J Neural Eng*, in revision

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Decoding Vowels and Consonants

Pei, Schalk et al., in preparation

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Associating Brain Activity with Cursor Movement

\[ \dot{y}(t) = g \left( P(t) - P_0 \right) \]
One-Dimensional BCI Control

Leuthardt, Schalk et al., J Neural Eng, 2004

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One-Dimensional BCI Control

Leuthardt, Schalk et al., *J Neural Eng*, 2004
Wilson, Schalk et al., *IEEE T Biomed Eng*, 2006
Felton et al., *J Neurosurg*, 2007
US Patent #7,120,486
International patent pending
Brain Control with Imagined Movements
Two-Dimensional BCI Control

Subj D (actual movement) vertical control (tongue) horizontal control (hand)

Subj E (imagined movement) vertical control (tongue) horizontal control (hand)

Schalk et al., J Neural Eng, 2008
Triggering Action with the Brain:
Clint Eastwood, 1982
Triggering Action with the Brain:
Clint Eastwood, 1982
Triggering Action with the Brain:
Brunner, Ritaccio, Schalk, 2009
Triggering Action with the Brain: Brunner, Ritaccio, Schalk, 2009
Using Imagined Vowels for Silent Communication

In collaboration with Eric Leuthardt, WashU
Using Imagined Vowels for Silent Communication

powered by BCI2000

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One more thing ...
One more thing...

Brain-Computer Interface World Record

G. Schalk, P. Brunner, Wadsworth/AMC

150 bits/min, 29 characters/min

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Waiting to start ...
Electrocorticographic Signals (ECoG) in Humans

- Characteristics
- ECoG
- Relationship

BCI Control

Diagnosis

- Open Questions
- Future Directions

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Invasive brain surgery (e.g., for epilepsy or tumors) requires mapping of function. Several techniques for functional mapping exist (e.g., fMRI, PET, electrical stimulation). All have substantial problems. We use ECoG and our BCI techniques (BCI2000, SIGFRIED algorithm) for real-time mapping.

Real-Time Mapping Example #1

Lateral X-Ray and ECoG Grids

Language Localization Using ECS Mapping (5 hours)

Language Localization Using SIGFRIED Mapping (several minutes)

60 sec

120 sec

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Real-Time Mapping Example #2

Motor Localization Using ECS Mapping (5 hours)

60 sec 120 sec

Motor Localization Using SIGFRIED Mapping (several minutes)

Example applications to date include motor, expressive/receptive language, and naming.

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Real-Time Mapping Example #3
Real-Time Mapping Example #3

Results from ECS after 2.5 hours

- Hand
- Tongue

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Real-Time Mapping Example #3

Results from ECS after 2.5 hours

Results from SIGFRIED
after 60 sec  after 180 sec

- Hand
- Tongue
Real-Time Mapping Example #3

Results from ECS after 2.5 hours

Results from SIGFRIED
after 60 sec  after 180 sec

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powered by BCI2000 and SIGFRIED technologies
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Brunner, Ritaccio, Schalk et al., Epilepsy and Behav, 2009
Electrocorticographic Signals (ECoG) in Humans

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Question 1: What is Gamma?

- **Candidate 1:**
  One oscillation (such as the mu rhythm)

- **Candidate 2:**
  “Brain Noise” with power-law characteristics

- **Candidate 3:**
  Many local oscillations

---

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Question 2: What is the LMP?
Question 2: What is the LMP?
Question (Set) 3: What is the best ...

- Location?
- Scale?
  (subdural, epidural, scull screws)
- Inter-electrode distance?
- Task?
  (decoding kinematic parameters vs. feedback)
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Current μECoG

Justin Williams, University of Wisconsin

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Next Generation $\mu$ECoG

Electronics integrated into platform

Justin Williams, University of Wisconsin
Different Design ...
What does all this mean?
Req. 1: Better Access to Brain Signals

Possible Number of Signals

(Spatial Resolution x Coverage)

Temporal Resolution (sec)

- $10^{-1}$
- $10^{0}$
- $10^{1}$

- EEG and single-neuron recordings
- fMRI

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Req. 1: Better Access to Brain Signals

Possible Number of Signals
(Spatial Resolution × Coverage)

Temporal Resolution (sec)

10^{-1} \quad 10^{0} \quad 10^{1} \quad 10^{2} \quad 10^{3} \quad 10^{4}

EEG and single-neuron recordings

fMRI
Req. 2: Better Interpretation

brain signals

behavior

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Req. 2: Better Interpretation

brain signals

brain signal grammar

behavioral grammar

behavior

a-priori information

a-priori information

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The Communication Problem Solved

The Brain and The Computer
much computational breadth
much computational depth
The hope is that, in not too many years, human brains and computing machines will be coupled together very tightly, and that the resulting partnership will think as no human brain has ever thought and process data in a way not approached by the information-handling machines we know today.

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ECoG presents an exciting opportunity for:

- Brain-computer interfaces
- Neuroscience research
- Clinical diagnosis
5th BCI2000 Workshop
Intl. Workshop on Advances in Electrocorticography

October 1-3, 2009
The Sagamore Conference Center
Bolton Landing, New York, USA

Invited Speakers
Peter Brunner, Wadsworth Center
Nathan Crone, Johns Hopkins Hospital
Christoph Guger, g.tec Medical Engineering, Inc.
Jeremy Hill, Max-Planck-Institute for Biological Cybernetics
Eric Leuthardt, Washington University School of Medicine
Robert Oostenveld, Radboud University Nijmegen
Anthony Ritaccio, Albany Medical Center
Steven Schachter, Harvard Medical School
Gerwin Schalk, Wadsworth Center
William Stacey, University of Pennsylvania
Jonathan Wolpaw, Wadsworth Center

Organization
Research Chair
Gerwin Schalk, Wadsworth Center
Clinical Chair
Anthony Ritaccio, Albany Medical Center
Registration and Contact
Jennifer Price, PriceJ@mail.amc.edu

http://www.bci2000.org

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Credits

Wadsworth Center, Albany
Sam Briskin, BS
Peter Brunner, MS
Aysegul Gunduz, PhD
Xiao-mei Pei, PhD
Adam Wilson, PhD

Albany Medical College, Albany
Anthony Ritaccio, MD
Timothy Lynch, MD
Joseph Emrich, MD

Washington University in St. Louis
Eric C. Leuthardt, MD
Daniel Moran, PhD

New York University, New York
Bijan Pesaran, PhD

University of Wisconsin, Madison
Justin Williams, PhD

University Medical Center, Utrecht
Erik Aarnoutse, PhD
Nick Ramsey, PhD

University of Washington, Seattle
Kai J. Miller, PhD
Jeffrey G. Ojemann, MD

Rensselaer Polytechnic Inst., Troy
Lester A. Gerhardt, PhD

University of Tübingen, Germany
Jürgen Mellinger, ME
Niels Birbaumer, PhD

US Army: W911NF-07-1-0415, W911NF-08-1-0216
NIH: R01-EB006356-01, R01-EB000856-06