Control of a two-dimensional movement signal by a noninvasive brain-computer interface in humans

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Overview of Major Points

- Non-invasive EEG-based method
- 2 almost-orthogonal degrees of freedom
- Online adaptation

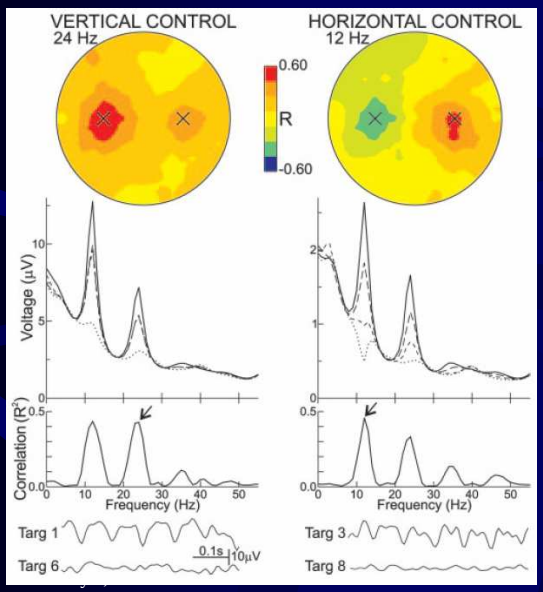
Outline

- Control Model
- Adaptation
- Experimental Methodology
- Results
- Conclusions

Control Model

- Berlin BCI uses β rhythm (8-11Hz)
- This adds μ rhythm (18-26Hz) for second dimension
- Linear combination of β and μ rhythms from left and right sensorimotor cortices
- Selection of specific bands from 1-D control trials

Control Model



- L (C3) & R (C4) electrodes used
- Plotted vs. R
- Frequency with highest correlation marked by arrow
- Example traces showing positive and negative directions

5

Control Model

- Control achieved via:

$$M_V = a_V (w_{RV} R_V + w_{LV} L_V + b_V)$$

$$M_H = a_H (w_{RH} R_H + w_{LH} L_H + b_H)$$

- Scaling factors and biases controlled online
  - Described in references unavailable on web
- Weights adapted online after each trial
- Seemingly used C3 and C4 for control in all cases, but not required by model

Adaptation

- Adaptation performed after each trial, starting with

$$\begin{bmatrix} M_V \\ M_H \end{bmatrix} = \begin{bmatrix} a_V & 0 \\ 0 & a_H \end{bmatrix} \left(\begin{bmatrix} w_{RV} & w_{LV} \\ w_{RH} & w_{LH} \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix} + \begin{bmatrix} b_V \\ b_H \end{bmatrix} \right)$$

$$\begin{bmatrix} w_{RV} & w_{LV} \\ w_{RH} & w_{LH} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

- Least mean-square (linear regression) to update weight values w_{XY}
- Each dimension quantized to target locations (4), updated independently
- Entire history used when updating values

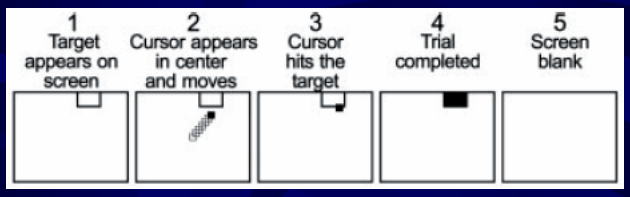
Adaptation

- Questions
  - Why not use orthonormal basis?
    - Could allow more principled analysis of results
    - May allow better comparison between users
  - Why not use window for updates?
    - Wanted to train system, but also let user learn
    - This method biased towards initial user behavior; cannot be completely retrained

Experimental Methodology

- Protocol
  - 64 electrodes referenced to right ear (not both)
  - 160Hz sampling rate, bandpassed (0.1-60Hz)
  - Each trial:
    - Target appears
    - 1s before cursor appears
    - 10s to reach target
      - Flash if successful, otherwise vanish
      - Blank screen for 1s between trials
    - Block Randomized

Experimental Methodology



If step 2 unsuccessful, jump to step 5

2-D Control

- Daily session was eight 3-min runs
- 1-min break between runs
- Start with 1-D control
- 2-D control added with one of:
  - Slow increase in magnitude of control in orthogonal direction
  - Alternate orthogonal 1-D runs, then jump to 2-D
  - Combination of both methods

Subjects

User	Age/Sex	Movement	Prior BCI Experience	Sessions
A	41/M	Midthoracic spinal cord injury (26 yrs)	91 hours	68
B	27/F	Full	1 hour	22
C	31/M	Full	None	40
D	23/M	Midcervical incomplete spinal cord injury (7 yrs)	19 hours (4 years earlier)	25

Results

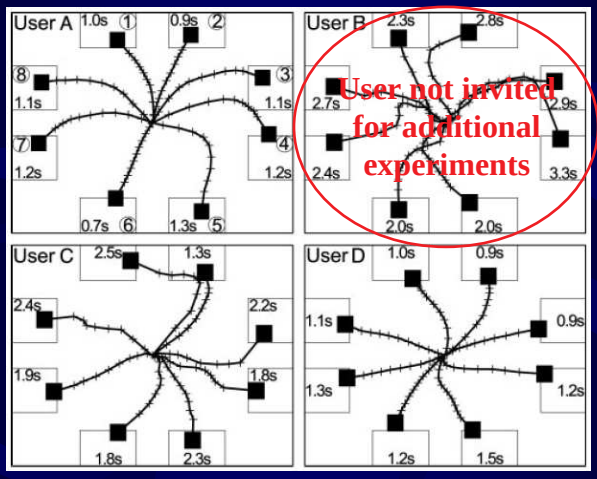
- Performance improved gradually
  - Implies long training time
- 83.6% overall success, 82.3% unweighted
  - Data from final 3 sessions for each user
  - More trials from top performing users

User	Success (last 3 sessions)	Average Time	Trials
A	89%	1.9s	742
B	70%	3.9s	521
C	78%	3.3s	528
D	92%	1.9s	717
Avg	82%	2.8s	626

Control and Target Position

Correlation (R^2)	A	B	C	D	Avg
Vertical × Y-pos.	0.44	0.31	0.40	0.54	0.42
Vertical × X-pos	0.00	0.00	0.01	0.01	0.00
Horizontal × Y-pos	0.48	0.29	0.27	0.54	0.40
Horizontal × X-pos	0.00	0.00	0.01	0.01	0.00

Average Trajectory by User



Additional Experiments

- 8 novel targets mixed with original 8
- 8 sessions with the new targets
- First session: 10% slower on average
- Remaining 7 sessions: 5% slower
  - Insignificant difference ($P>0.05$)
- Also, EMG on muscle groups showed insignificant correlation with control

Comparison with Invasive Methods

Study (Lab)	Best Average Movement Time	Target as % of workspace	Hit rate
Serruya *et al.* (Donoghue)	1.5s	2.3	?
Taylor *et al.* (Schwartz)	1.5s	1.3	86%
Carmena *et al.* (Nicolelis)	2.2s	7.7	89%
This paper	1.9s	4.9	92%

- Results are for each study's best user
- Other studies used nonhuman primate necessitating alternate protocols

Conclusions

- Demonstrated effective 2-D EEG control
- Results far superior to earlier work by group
  - Higher correlation with correct dimension
  - Lower correlation with incorrect dimension
- Results competitive with invasive approaches

Conclusions

- Best average trial time of 1.9s
  - 2 dimensions, 4 values each
  - ITR of 126 bits per minute (?)

$$\frac{60s}{min} \times \frac{trial}{1.9s} \times \frac{4bits}{trial}$$

- Favorite line:
  - "The present methods applied to ECoG activity could constitute a *minimally invasive* BCI that might ultimately yield the best results" (accuracy with less risk)