BCI within an AAC framework

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Topics to touch on

1. BCI as one option within the AAC system
2. The RSVP Keyboard™ BCI
3. Clinical screening for BCI
4. Learning to use a BCI for spelling
   - Mastery task
   - Attention training
5. User feedback
   1. User centered design
   2. Patient centered outcomes
6. The role of the clinical researcher and communication specialist
Locked In Syndrome:  
American Congress of Rehab Med (1995)

- A syndrome characterized by preserved awareness, relatively intact cognitive functions, and ability to communicate while being paralyzed and voiceless. This syndrome is defined by five criteria:
  1. Sustained eyes opening and preserved vertical eye movement
  2. Preserved higher cortical functions
  3. Aphonia or severe hypophonia
  4. Quadriplegia or quadriparesis
  5. Primary mode of communication that uses vertical eye movements or blinking
Classifications of LIS

- **Complete or total LIS**: Quadriplegia and anarthria. No eye movement
- **Classic LIS**: Preserved vertical eye movement and blinking
- **Incomplete LIS**: Recovery of some voluntary movements in addition to eye movements (Bauer et al, 1979)
Epidemiology of LIS

- Over 2 million people in the U.S. with some level of functional LIS;
- Less than 1% of CVA;
- More than 85% of individuals are still alive after 10 years;
- Average age range: 17 – 52 years;
- Younger patients have better px of survival.
Common Diagnoses Leading to LIS

- End stage ALS
- Brainstem CVA
- High level spinal cord injury
- Traumatic Brain injury
Expanding LIS diagnoses by function: severe speech and physical impairment (SSPI)

- Cerebral palsy
- Muscular dystrophies
- Multiple sclerosis
- Parkinson’s disease
- Parkinson’s plus
  - Progressive Supranuclear Palsy (PSP)
  - Multiple System Atrophy (MSA)
- Tumors
- Progressive ataxias
  - Cerebellar ataxia
Options for restoring functional motor function

- Rely on capabilities of remaining pathways
  - Eye gaze communication system
  - Head mouse access to computer
- Detouring around neural pathway breaks
  - FES: Direct electrical stimulation of paralyzed muscles through EMG activity in muscles above lesion level.
- Provide the brain with a new, non-muscular communication and control channel: BCI.
Need for AAC

- Another option within a person’s augmentative communication system
- MUST consider
  - Language system
  - Access method
Augmentative Communication Approaches

**Unaided Approaches**
- Speech
- Vocalization
- Gestures
- Eye gaze
- Body language
- Sign language

**Aided Approaches**
- Paper and pencil
- Communication books
- Communication boards and cards
- Speaking computers and mobile technology
- Talking typewriters
- Speech generating devices
The AAC System for individuals with SSPI

- Spelling device with BCI
- SGD with eye tracking
- Eye gaze
- Eye blinks
- Vocalization
BCI for spelling: different paradigms

- Row-column presentation with oddball paradigm
Translational R01 from NIDCD

Signal Processing Engineering

Neurophysiology

Computer Science (language modeling)

Clinical team

Northeastern U group:
Deniz Erdogmus, PhD
Umut Orhan, PhD
Murat Sina

Barry Oken, MD
Meghan Miller, BA
Roger Ellingson, MS

Brian Roark, PhD
Andrew Fowler
Steven Bedrick, PhD
Kyle Gorman, PhD

Melanie Fried-Oken, PhD
Barry Oken, MD
Aimee Mooney, MS CCC/SP
Betts Peters, MS CCC/SP
GB, participant with LIS
JS, participant with ALS
The RSVP Keyboard™
RSVP BCI Overall Goal

To integrate new engineering developments in EEG analysis with language models for people who are functionally locked-in to communicate and control their environments.
Unique aspects of OHSU BCI research

1. RSVP: stimulus presentation
2. Language modeling & EEG fusion
3. End users with SSPI (not only LIS)
4. Participatory Action Research
5. Language mastery tasks
6. Clinical BCI perspective
   1. Screening
   2. Training
   3. User within the loop
BCI Triangulated Collaboration

Meetings:
- Consensus building for decisions
- Confirm changes with group

Language Modeling Team

Language model building with user vocabularies and customization per user

User Interface Team
- Cognitive factors
- Patient information
- Presentation

Signal processing Team
- EEG classification

Probability matrix for intent decisions from EEG

USER TRIALS
(Clinical team)
RSVP Keyboard: Spelling stimuli for a P300 signal

- RSVP:
  - Rapid
  - Serial
  - Visual
  - Presentation of letters

- 400ms per letter
RSVP Keyboard™: A Spelling Interface based on the P3 Signal

- A sample 1-sequence training epoch...
- Multiple sequences of same letters shuffled
  => multi-trial ERP detection

Subject controls
epoch start time

1000ms 400ms

Deniz Erdogmus, Cognitive Systems Laboratory, Northeastern University
LANGUAGE MODELING
Word completion from language corpora

Technology-assisted spelling after # letters (n-gram prediction)

1: Automatic completion          2: Self-select from a list
RSVP Keyboard: Fusing Language Model & EEG Evidence

- RSVP Keyboard makes letter selections based on **joint evidence** from an n-gram language model and EEG signals.

- Language model is trained using large language databases:
  - *Wall Street Journal* and *New York Times* databases
  - Enron e-mails
  - User-provided previous conversations and vocabulary lists
Training Mode

Gathering Data to Train Classifier
(about 15 minutes)

- Subject instructed to look for a specific letter
- 50 series containing 2 sequences that present 30 characters (26 letters and 4 symbols)

Machine Learning
(about 15 minutes)

Learning Algorithm + EEG

Creation of the EEG/P3 Classifier

Writing Mode

Copy Task or Sentence Formulation

Subject presented with sequences of possible letters and attempts to write whatever they wish.

Hybrid Classifier

EEG/P3 Classifier
Language Model

Prediction and typing of intended letter
Measuring Speed and Accuracy

– Highest level completed on a copy-spelling task
– Selection accuracy score
  • Correct characters/minute
  • Total error rate
Measuring AUC for system accuracy

Calibration

• Every time the user puts on the cap, the system must determine what a ‘keystroke’ selection is.
• The computer learns the difference between a ‘target’ and a ‘non-target’.
  – A variable is created that predicts classifier accuracy by estimating the area under the curve (AUC) of true positive vs. false positive rate for target vs. non-target classification.
The Mastery Task for Copy-Spelling

- Word copying task to optimize user performance.
- Words embedded in phrases presented one at a time on laptop screen, above RSVP Keyboard™.
- Target words contain 4 letters and vary in LM predictability.
- Mastery task has 5 levels of difficulty, determined by degree of support from LM. At higher levels, target letters have lower probabilities, so LM provides less support and stronger EEG responses are required for correct selections.
- Each level includes 3 sets of 3 phrases.
- Words in different positions in sentences.
- Goal: successfully copy 2/3 words at each level.
- Mastery task continues until participant either completes all 5 levels or fails to pass a lower level.
Measuring spelling accuracy and speed

Improvement measures

<table>
<thead>
<tr>
<th>Target</th>
<th>Output</th>
<th>Time: 4:10</th>
<th>Characters in output: 11</th>
<th>Incorrect selections: 6</th>
<th>Total selections: 17</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITH</td>
<td>SAR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CITY</td>
<td>CITY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HILL</td>
<td>HILL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Typing rate $= \frac{\text{output}}{\text{seconds}} \times 60 = \frac{11}{4.10} \times 60 = 2.64$  
Error rate $= \frac{\text{incorrect}}{\text{total}} = \frac{6}{17} = 35.3\%$
Free spelling task

- Participant describes a line drawing
- Task ends when participant indicates phrase is complete or after 10 minutes
- Message is confirmed. Participant is asked, “Is that what you meant to type?”

Line drawings from Northwestern Anagram Test
(Weintraub, Mesulam, Thompson)
CLINICAL ASSESSMENT OF FUNCTIONALLY LOCKED-IN SUBJECTS FOR RSVP BCI

Screening tool criteria*

1. Assess *requisite skills* for RSVP Keyboard
   1) Vision
   2) Hearing
   3) Language (Auditory & Reading Comprehension; Spelling)
   4) Sustained Visual Attention

2. Easy to administer
3. Less than 45 minutes total time
4. Completed at participant’s residence, at bedside or wheelchair

*Cannot use for Complete LIS participants*
Sources for Assessment Design

- **Boston Naming Test**, Kaplan, Goodglass, and Weintraub, 1983
- **Functional Linguistic Communication Inventory**, Bayles and Tomoeda, 1994
- **Boston Assessment of Severe Aphasia**, Helm-Estabrooks, Ramsberger, Morgan, Nicholas, 1989
- **Coma Recovery Scale-Revised**, Giacino, Kalmar, 2004
- **Western Aphasia Battery-Revised**, Kertesz, 2006

Ergonomic information regarding computer monitor distance and angle taken from: *The United States Department of Labor; Occupational Safety & Health Administration OSHA.*
Confirm consistent and reliable YES/NO

• Binary code:
  – Eyes (up/down; left/right)
  – Eye blink
  – Thumb up/down
  – Smile/pucker
A. Questions to care providers
1. Does patient wear glasses? Recent prescription?
2. Do they see well enough to read?
3. Any other visual problems (cataracts, macular degeneration, field cut)?

B. Diplopia: present?

C. Visual Perception: Computer-based task for central accuracy and peripheral accuracy
1. Questions about hearing function to participant (y/n response)
2. Questions to care provider about participant’s hearing function
3. Tuning fork test
Language: Auditory comprehension

A. Object Related Eye Movement Commands
Look at the (object) X4

B. Non-Object Related Eye Movement Commands
Look away from me
Look up/down (at ceiling/floor)

C. Visually based Situational Orientation (yes/no response)
Am I touching my ear/nose right now? X4

D. Personal Orientation
Name, age, history

E. Yes/No to Complex Sentences
“Does a stone sink in water?”
Language
Reading Comprehension and Spelling

1. Object-picture matching X4
2. Picture-word matching from field of 4
3. Letter identification X4
4. Eye pointing to first letter of a word X4
   Bed  J  M  B  A
5. Spelling words with eye gaze boards (want, ball, stop)
• E-TRAN board for yes/no responses
Cognition: Sustained Visual Attention

- RSVP Task created on EPRIME software
- Yes/no response to identify when a certain letter is present on the screen.
- Correct target and 3 foils/trial
- Must respond accurately in 9/10 trials
9 participants with SSPI; 9 matched controls

<table>
<thead>
<tr>
<th></th>
<th>LIS</th>
<th>CONTROLS</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, mean (range)</td>
<td>45.8 (27-65)</td>
<td>45.2 (17-66)</td>
<td>0.965&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>7/2</td>
<td>4/5</td>
<td>0.147&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ethnicity (%Caucasian)</td>
<td>77.8</td>
<td>100</td>
<td>0.134&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Years of education (range)</td>
<td>14.6 (12-23)</td>
<td>18.2 (11-22)</td>
<td>0.067&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>First language English (n)</td>
<td>8</td>
<td>9</td>
<td>0.303&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Level of familiarity with computer(some/expert)</td>
<td>4/5</td>
<td>2/7</td>
<td>0.317&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Type of LIS (n)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incomplete</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classical</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Years since LIS onset</td>
<td>14.8 (1-55)&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Mann-Whitney test.  <sup>b</sup> Chi-square test.  
<sup>c</sup> Years since LIS onset was calculated for all participants since diagnosis, either classical or incomplete LIS. The cause of LIS was ALS (4), brainstem stroke (2), cerebral palsy (1), brainstem AVM (1), and Duchenne muscular dystrophy (1).
BCI Screening

- Clinical screening for use of BCI as an AAC access method is feasible.
- An adapted screening tool has been developed and should be administered to gain important clinical information about potential users with SSPI.
Learning to Use a BCI
Preparing for independent BCI use at home: How can we help people learn to use BCI?
Learner in the Loop:
What skills does the learner bring to the BCI task?
What affects user performance?

Lack of reliable performance by BCI users is a common problem.

- Cognitive status
- Medications
- Pain
- Motivation
- Language and literacy

Polin and Kok, 1995
PROCESS-SPECIFIC ATTENTION TRAINING
Process-Specific Attention Training

• We adapted an evidence-based direct attention training program developed for people with TBI

• Attentional abilities can be improved by providing structured opportunities for exercising particular domains of attention

Sohlberg & Mateer, 1987; Sohlberg et al., 2000
Attention Training for the RSVP Keyboard™

- Independent home practice with a series of video simulations of RSVP Keyboard™ task
- 3 sessions each week
- Each 30-minute session includes 3 calibration simulations
- Videos contain random animal photo. Presented to assess wakefulness and vigilance. At the end of each simulation, the participant is asked whether s/he saw an animal.
## Pilot study: 2 participants

<table>
<thead>
<tr>
<th></th>
<th>KM</th>
<th>JS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
<td>63</td>
<td>70</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td>Male</td>
<td>Male</td>
</tr>
<tr>
<td><strong>Diagnosis</strong></td>
<td>ALS (bulbar onset)</td>
<td>ALS (limb onset)</td>
</tr>
<tr>
<td><strong>Date of diagnosis</strong></td>
<td>2007</td>
<td>2011</td>
</tr>
<tr>
<td><strong>RSVP screening</strong></td>
<td>100% on all tasks</td>
<td>100% on all tasks</td>
</tr>
<tr>
<td><strong>Eye movement</strong></td>
<td>Within normal limits</td>
<td>Within normal limits</td>
</tr>
<tr>
<td><strong>Upper extremity</strong></td>
<td>Severely impaired; able to click</td>
<td>Impaired; able to control</td>
</tr>
<tr>
<td><strong>movement</strong></td>
<td>switch with fingertips on right hand</td>
<td>wheelchair joystick and computer trackball</td>
</tr>
<tr>
<td><strong>Mobility</strong></td>
<td>Power wheelchair with caregiver controls</td>
<td>Power wheelchair</td>
</tr>
<tr>
<td><strong>Respiration</strong></td>
<td>Tracheostomy &amp; mechanical</td>
<td>Noninvasive ventilation (BiPAP with nasal pillow mask)</td>
</tr>
<tr>
<td></td>
<td>ventilation</td>
<td></td>
</tr>
<tr>
<td><strong>Speech</strong></td>
<td>Anarthric</td>
<td>Within normal limits</td>
</tr>
<tr>
<td><strong>Communication</strong></td>
<td>Yes/no eye movement signals; SGD with eye tracking or switch scanning</td>
<td>Speech</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Positioning for</strong></td>
<td>Reclined in bed</td>
<td>Seated in power wheelchair</td>
</tr>
<tr>
<td><strong>BCI use</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Participant Inclusion Criteria

- Dx of acquired neuromuscular or neurodevelopmental disorder
- 18 - 80 years of age
- Able to participate in 1-3 hour experimental interactions
- Literate in English and capable of spelling words
- WNL or corrected vision and hearing
- Speech that is understood less than 25% of the time OR minimal reliable motor response
- Pass the RSVP Keyboard™ screening tool
Study design

• Small n study design: Multiple-baseline across participants
• Baseline performance established with 5+ weekly data-collection visits
• Length of baseline phase varies for each participant
• 6-week intervention phase begins after final baseline visit (home practice 3x/week)
• Weekly data-collection visits continue through intervention phase
Data-collection visits

- Each visit includes:
  - PROMIS General Health questions
  - N-back task
  - RSVP Keyboard™ calibration
  - RSVP Keyboard™ Mastery task
  - User Feedback Questionnaire

- During intervention phase, researchers collect data on completion of home practice activities (from participant report and tracking software)
N-back task

• Common working memory assessment task
• 20 series of 20 letters presented one at a time (RSVP format)
• In each series, the participant looks for an “n-back”: a letter that matches the one presented $n$ letters previously
  – 1-back: E H D A A V I W N P
  – 2-back: K R Q C I E L E P D
  – 3-back: P B M E B Y H I R L
• After each series, participant is asked, “Did you see an n-back?”
Variables

- N-back score
- Calibration AUC (area under the curve of true positive vs. false positive rate for target vs. non-target classification)
- Highest mastery task level completed
- Selection accuracy: \( \frac{\text{# of correct selections}}{\text{total # of selections}} \)
- Typing rate: \( \frac{\text{# of correct selections}}{\text{minute}} \)
- Covariates:
  - Health, emotional state, pain, fatigue (PROMIS)
Pilot study results: KM

• Completed 4 baseline sessions
• Demonstrated excellent performance on all tasks, including typing with RSVP Keyboard™
• Completed level 5 Mastery Task in weeks 1 & 2; moved on to picture description free spelling in subsequent 2 visits.
• Did not complete intervention phase – no need for attention training to improve performance
Pilot study results: KM
N-back and AUC

Reached 85% accuracy on 3-back task (very difficult)

Mean: .80
Range: .75-.85
Scores > .75 are typically sufficient for accurate RSVP Keyboard™ typing
• KM teaches us that attention can be dissociated from learning requirements for BCI. He does not have a need to increase attention for this task.
Pilot study results: JS

- Completed 5 baseline sessions
- Began intervention phase (now in week 4 of 6)
Pilot study results: JS N-back

- Stable baseline ≈80% on 2-back task
- Improved to 90% in intervention phase
Pilot study results: JS AUC

- BL Mean: .62
- BL Range: .57-.67
- No significant improvement in intervention phase
- Scores < .70 are typically not sufficient for accurate RSVP Keyboard™ typing
Pilot study results: JS
Highest mastery level completed

- BL: completed level 1 or 2
- No improvement and inconsistent performance in intervention phase
Next steps

• Complete study with 5+ participants
• Explore other interventions
  – Mindfulness meditation
  – Modified stimuli (e.g. colorful letters)
• Does n-back performance predict RSVP Keyboard™ performance?
• How can we customize interventions for each BCI user?
Input from participants with LIS
John and Greg as expert consultants
Patient Centered Outcomes for BCI
“Through this research project, I have had the opportunity to assist the team in understanding things from a user’s standpoint. It has shaped my concept of what I think would be most helpful, not only for me, but for others who are locked-in. This has been, and continues to be, a wonderful experience for me.” GB
“Giving people with LIS the option to use a BCI in their daily life can provide so many benefits. It has the potential to give us a sense of control, the ability to communicate independently, and a sense of depth. The challenges of designing a BCI system for people who are social and intelligent are making it user friendly, reliable, just as easy and fast as our current communication method, and low-profile.”
“At the very least, I am hoping to get aid in communication from a BCI system. I want to be able to express myself without the help of others at all times. If the system were able to predict text based on how my sentences are formed, that would be helpful. I want to be able to write emails and use Facebook independently. For people like me who are completely locked-in, it would also be nice to be able to control simple things in my environment like my wheelchair and the lift on my van. I would like to turn on lights, the thermostat, the radio, and my television. As I work more with the BCI system, I feel that it has the potential to do an unlimited amount of things in the future.”
References


RSVP team references


“BCI also can open new doors, which is hard to do when you’re literally locked-in.” GB
This research was supported by NIH Grant #1R01DC009834-01. Melanie Fried-Oken, PhD, P.I. OHSU IRB # 4863