The RSVP Keyboard™: A Brain Computer Interface for Users who have Locked-in Syndrome

Melanie Fried-Oken, D. Erdogmus, A. Mooney, B. Peters, B. Orhan, B. Oken, B. Roark
Neurology, Biomedical Engineering and Institute on Development and Disabilities
Portland, OR
ISAAC
July, 2012

Introduction to BCI

Brain-Computer Interface (BCI)

- Technology whereby a computer detects a 'selection' made by a person who does not rely on neuromuscular activity.
- The technology uses the person’s changes in brain activity as the intended execution.
- Technology substitutes for the loss of typical neuromuscular outputs so that people can interact with their environments through brain signals rather than through muscle movement.

Reference:

- 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 eye 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 involving 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)

**Common Diagnoses Leading to LIS**

- End stage ALS
- Brainstem CVA
- High level spinal cord injury
- Traumatic Brain injury

**Functional LIS diagnoses**

- All of Common
  - Cerebral palsy
  - Muscular dystrophies
  - Multiple sclerosis
  - Parkinson’s disease (plus)
  - Tumors

**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 potential of survival
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.

Current human BCI research for communication & control

- Non-invasive BCI: Braingate
- Invasive BCI: Braingate

Current BCI Research

BCI 2000 with P300 speller

- Most commonly used spelling interface
- Uses a grid with randomly flashing rows/columns
- 3 passes of same response = selection

Berlin BCI: Hex-o-spell

RSVP Keyboard™ BCI Project
RSVP Keyboard™: BCI for Users who have Locked-In Syndrome

RSVP Keyboard™
- Rapid
- Serial
- Visual
- Presentation

Brain-Computer Interface with RSVP Keyboard™
Allows user to communicate independent of neuromuscular output by tracking selections via changes in EEG activity.

RSVP Keyboard™ 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.

OHSU RSVP Keyboard™ BCI Project

Unique Aspects of OHSU BCI Research
1. RSVP: stimulus presentation
2. Language modeling
3. Single event ERP goal
4. Functionally locked-in patients
5. Participatory Action Research
6. User-Centered Design
7. Community Based

“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

ISAAC 2012
Pittsburgh, PA
BCI Triangulated Collaboration

Signal Processing and Interface Design

Non-invasive, wet electrode BCI

Photic stimulation at 1 Hz during routine EEG

P300 Response
- Involuntary spike in EEG activity over the parietal cortex
- Indicates a salient, infrequent event following frequent/routine stimuli

P300 is a variable waveform
- Sensitive to alertness and attention
- Amplitude increased by stimulus infrequency and stimulus salience
- Latency affected by target detection difficulty and age
RSVP™ and P300

Language Modeling

RSVP™ and P300

What is a language model?

- RSVP Keyboard™ BCI presents single symbols
- Assigns each symbol a probability of being next
  - Suppose user has typed: “the Pittsburgh Pi”
  - Then probability of r should be high; e maybe not so high but not very low; q should be low but not zero
- Builds statistical models to predict symbols given previously typed symbols
  - Estimates probabilities from collected text
  - Also needs to include probability for delete

Word models

- We build models that predict the current word
- Users still able to type words never seen before
  - Estimation methods give no zero probabilities
- Collect evidence for symbols from words
  - Suppose user has typed: “the Pittsburgh Pi”
  - Possible next words: Pirates, Pie, Pilots, Pickles
  - Thus possible (high probability) next letters: r, e, l, c
- Thus this is an “open-vocabulary” system
  - Can incorporate word-completion easily

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

Use of language model in BCI system

- LM probabilities can be used several ways
  - Fusion within ERP detection classifier (yes)
    - Aiding classification; contributing to stopping criteria
  - To select subset of symbols to display (not yet)
    - This is related to assigning the optimal code
  - To add strings (words) to display (not yet)
  - Soft keyboard: select sets of symbols (not yet)
  - Recover gracefully from spelling errors (not yet)
RSVP Keyboard™: BCI for Users who have Locked-In Syndrome

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

Deniz Erdogmus, Cognitive Systems Laboratory, Northeastern University
Fried-Oken, et. Al
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RSVP Keyboard™: BCI for Users who have Locked-In Syndrome

Bayesian Fusion for Calibration

User Centered Design
Participatory Action Research
Community Based

HB and GB as expert consultants
"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 be nice to be able to control simple things 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." — 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." — HB

**Participants**

**People with LIS/FLIS Summary**
- **Gender:** 10 male, 2 female
- **Age:** $M = 45.5 \text{ yrs}$
- **Diagnosis:** 5 ALS, 2 brainstorm stroke, 2 cerebral palsy, 1 Traumatic Brain Injury, 1 Spinal Cerebellar Ataxia, 1 Duchenne Muscular Dystrophy
- **Status Post:** (7) 2-10 yrs, (2) >10 yrs, (3) lifetime
- **LIS Type:** 1 Total, 8 Incomplete, 3 Functional
- **Education:** $M = 15.58 \text{ yrs}$
- **Residence:** 7 home, 5 adult foster home

**Inclusion Criteria**
1) **People with LIS or FLIS**
   - Dx of acquired neuromuscular or neurodevelopmental disorder
   - 18 - 75 years of age
   - Capable of participating 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
2) **Controls**

**People with LIS/FLIS (N=12)**

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age</th>
<th>Dx</th>
<th>S/P</th>
<th>LIS Type</th>
<th>Edu</th>
<th>Profession</th>
<th>Residence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male*</td>
<td>42</td>
<td>ALS</td>
<td>2 yrs</td>
<td>Incomplete</td>
<td>19 yrs</td>
<td>Architect</td>
<td>Home with wife/child</td>
</tr>
<tr>
<td>Female</td>
<td>65</td>
<td>ALS</td>
<td>6 yrs</td>
<td>Functional</td>
<td>14 yrs</td>
<td>Homemaker/ Volunteer</td>
<td>Home with husband</td>
</tr>
<tr>
<td>Male</td>
<td>43</td>
<td>ALS</td>
<td>11 yrs</td>
<td>Incomplete</td>
<td>14 yrs</td>
<td>Business</td>
<td>Home with wife/children</td>
</tr>
<tr>
<td>Male</td>
<td>40</td>
<td>ALS</td>
<td>5 yrs</td>
<td>Incomplete</td>
<td>23 yrs</td>
<td>Physician</td>
<td>Home with wife/children</td>
</tr>
<tr>
<td>Male</td>
<td>49</td>
<td>ALS</td>
<td>4 yrs</td>
<td>Incomplete</td>
<td>12 yrs</td>
<td>Sales</td>
<td>Private</td>
</tr>
<tr>
<td>Male</td>
<td>43</td>
<td>BS CVA</td>
<td>16 yrs</td>
<td>Incomplete</td>
<td>14 yrs</td>
<td>Landscaper</td>
<td>Home with parent</td>
</tr>
<tr>
<td>Male</td>
<td>41</td>
<td>BS CVA</td>
<td>2 yrs</td>
<td>Total</td>
<td>18 yrs</td>
<td>Engineer</td>
<td>AFH</td>
</tr>
</tbody>
</table>

*Deceased
People with LIS/FLIS (N=12)

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age</th>
<th>Dx</th>
<th>S/P</th>
<th>LIS Type</th>
<th>Edu.</th>
<th>Profession</th>
<th>Residence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>50</td>
<td>CP</td>
<td>NA</td>
<td>Incomplete</td>
<td>12</td>
<td>SSDI</td>
<td>AFH</td>
</tr>
<tr>
<td>Female</td>
<td>55</td>
<td>CP</td>
<td>NA</td>
<td>Functional</td>
<td>12 yrs</td>
<td>SSDI</td>
<td>AFH</td>
</tr>
<tr>
<td>Male</td>
<td>30</td>
<td>TBI</td>
<td>2 yrs</td>
<td>Incomplete</td>
<td>16 yrs</td>
<td>Musician</td>
<td>AFH</td>
</tr>
<tr>
<td>Male</td>
<td>82</td>
<td>Spinal Cerebellar Ataxia Duchenne MD</td>
<td>8 yrs</td>
<td>Incomplete</td>
<td>21 yrs</td>
<td>Attorney</td>
<td>Private</td>
</tr>
<tr>
<td>Male</td>
<td>27</td>
<td>Duchenne MD</td>
<td>NA</td>
<td>Functional (+ speech)</td>
<td>12 yrs</td>
<td>SSDI</td>
<td>AFH</td>
</tr>
</tbody>
</table>

Control Summary

- 14 healthy controls
- 6 males, 8 females
- 17-66 years old (M = 42)
- Level of Education: 11-23 years
- Profession: Student, Computer programmer, Accountant, Physical Therapist, Academic Advisor, Graphic Designer, SLP (3), Researcher.

Screening tool criteria

1. Assess requisite skills for RSVP Keyboard™
2. Easy to administer; uses laptop computer & eye-gaze board
3. Approximately 1 hour to administer
4. Completed at participant’s residence, at bedside or wheelchair
5. Need to confirm consistent & reliable YES/NO; establish binary code (eye blink, eye up/down, left/right, pucker/smile)

Screening cannot be used for Complete or Total LIS participants

Sources for screening tool design

- Boston Naming Test, Kaplan, Goodglass, and Weintraub, 1983
- Functional Linguistic Communication Inventory, Bayles and Tomaeda, 1994
- Boston Assessment of Severe Aphasia, Helm, Estabrooks, Rasmberger, 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.

BCI screening tool: requisite skills for RSVP™ Keyboard

A. Current yes/no signals
B. Hearing: Questions to participants & care providers
C. Pain: Questions to participants & care providers
D. Vision:
1. Questions to participants & care providers
2. Visual Perception: Computer-based task for central accuracy and peripheral accuracy
E. Communication:
1. Auditory Comprehension
2. Reading Comprehension and Literacy
3. Spelling
F. Cognition:
1. Questions to participants & care providers
2. Sustained Visual Attention: Computer-based with adaptability for speed of information processing and working memory capacity (slower rate/fewer symbols)
G. Motor: Physical Therapy input on optimal BCI positioning and description of current motor skills

Screening: Summary to Date

- Screening has been used with 10/12 participants and controls
- Can be completed with individuals with a variety of diagnoses
- Can be completed in one session for most participants
### RSVP™ Task Sequence

1) **Calibration** - System instructs participant to look for a specific letter to train the classifier

2) **Letter Generation Tasks**
   - **Mastery** – A series of exercises to improve ability to use BCI RSVP Keyboard™ (levels 1-5)
   - **Copy** – A word-copy task

3) **Free Writing** - Participants use the system to write whatever they wish

### Calibration Task

**Gathering Data to Train Classifier** (about 12 minutes):
- Subject instructed to look for a specific letter
- 75 or 50 series containing 10 letters or symbols, including the target letter
- Machine Learning: Learning Algorithm + EEG

**Creation of the EEG/P3 Classifier**
- Hybrid Classifier
  - EEG/P3 Classifier
  - Language Model

### Methods

- Document conditions which may affect p300*:
  - Pain
  - Medication changes
  - Recent illness and/or hospitalization
  - Scalp conditions
- Instruction period with demonstration
- Initial Stanford Sleepiness Scale (SSS) rating
- Series of calibration trials with SSS rating taken after each trial
- Opportunity for mastery with best calibration


### Stanford Sleepiness Scale

<table>
<thead>
<tr>
<th>Degree of Sleepiness</th>
<th>Scale Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeling active, vital, alert, or wide awake</td>
<td>1</td>
</tr>
<tr>
<td>Functioning at high levels, but not at peak; able to concentrate</td>
<td>2</td>
</tr>
<tr>
<td>Awake, but relaxed; responsive but not fully alert</td>
<td>3</td>
</tr>
<tr>
<td>Somewhat foggy, let down</td>
<td>4</td>
</tr>
<tr>
<td>Foggy; losing interest in remaining awake; slowed down</td>
<td>5</td>
</tr>
<tr>
<td>Sleepy, woozy, fighting sleep; prefer to lie down</td>
<td>6</td>
</tr>
<tr>
<td>No longer fighting sleep, sleep onset soon; having dream-like thoughts</td>
<td>7</td>
</tr>
<tr>
<td>Asleep</td>
<td>X</td>
</tr>
</tbody>
</table>

http://www.stanford.edu/~dement/sss.html
Pain interference questions*

- How difficult was it for you to take in new information because of pain today?
- How much does pain interfere with your ability to concentrate today?
- How often is your pain so severe you could think of nothing else today?
- How often does pain make you feel discouraged today?
- How much does pain interfere with your ability to remember things today?

* Adapted from PROMIS item Bank v1.0 – Pain Interference, https://www.assessmentcenter.net/ac1//files/pdf/8f0480790a2246da971107687d492259.pdf

Selection Strategies

- **Motor**: Think about your hand clicking a mouse or reaching out to grab the target letter
- **Speech**: Scream the letter in your mind or think YES! or BAM! for the target letter
- **Visual**: Imagine a net “catching” the target letter, or Mario running along and jumping up to hit the target letter
- **Symbol**: Visualize a happy face for the target letter
- **Sensory**: Think about cold and then about warmth for the target letter
- **Auditory**: Think about a certain sound or song for the target letter

Selection Strategies Reported (N = 26)

**People with LIS/FLIS**

- **Sensory**: Imagining pinching self for target letter
- **Speech**: “BAM” for target (multiple)
- **Visual**: “Think of seeing boobs when I see the target letter”
- **No strategy**

**Controls**

- **Motor**: Swinging a golf club, Sword slashing, Punching the letter
- **Speech**: “BAM” for target; (multiple)
- **Visual**: “Think of letter exploding”

**PLIS**

- **Sensory**: Imagining pinching self for target letter
- **Speech**: “BAM” for target; (multiple)
- **Visual**: “Think of letter exploding”

Calibration Results

**AUC** 0.9183

Estimated Probability of Success

Selected Probability of Success: PLIS

Selected Probability of Success: Controls

Range and Average of Probability of Success: PLIS

Range and Average of Probability of Success: Controls
Mastery: LM assisted & structured copy task

Goals of the Mastery Task
- To give practice opportunity to improve performance with the RSVP Keyboard™
- To allow participants to experience success with the system early on
- To incorporate the concept of errorless learning into the RSVP™ paradigm

Mastery Task: Design
- Participants are presented with a pre-selected set of phrases, one at a time
- Task is to copy a target word from each phrase
- 5 levels of difficulty
  - Earlier levels provide more support from the language model, so participant can spell successfully even if brain signals are not optimal
- Participant must complete 2 out of 3 phrases at each level
- 3 sets of phrases at each level so participant can re-attempt levels if necessary

Mastery Task: Stimuli
- Chosen by LM team from MacKenzie & Soukoreff (2003)’s set of 500 balanced phrases of text
- Phrases 3-6 words long
- Target words 3-4 letters long
- Target word always appears second or later in phrase so preceding word(s) provide information to language model


Mastery Task: Sample Phrases
- Level 1 (maximal support from LM)
  - I DO _NOT_ AGREE
  - GO TO _THE_ MOVIES
  - MUSIC _AND_ LAUGHTER

- Level 5 (minimal support from LM)
  - A CAN OF _FLEA_ POWDER
  - SHE NEVER _AIMS_ OFF THE MARK
  - SOMETHING THAT _BUYS_ US TIME
RSVP Keyboard™: BCI for Users who have Locked-In Syndrome
GO_TO_THE_MOVIES
GO_TO_

GO_TO_THE_MOVIES
GO_TO_

GO_TO_THE_MOVIES
GO_TO_

GO_TO_THE_MOVIES
GO_TO_

GO_TO_THE_MOVIES
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GO_TO_
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<table>
<thead>
<tr>
<th>GO_TO_THE_MOVIES</th>
<th>GO_TO_THE_MOVIES</th>
</tr>
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<tbody>
<tr>
<td>U</td>
<td>J</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GO_TO_THE_MOVIES</th>
<th>GO_TO_THE_MOVIES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>GO_TO_THE_MOVIES</th>
<th>GO_TO_THE_MOVIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Z</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>S</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>B</td>
</tr>
<tr>
<td>G</td>
<td>X</td>
</tr>
</tbody>
</table>
RSVP Keyboard™: BCI for Users who have Locked-In Syndrome
**Mastery Task: Stopping Criteria**

- RSVP Keyboard™ will move on to next phrase when one of the following criteria is met:
  - Target word is spelled correctly
  - Participant has spent 10 minutes attempting to type target word
  - Number of sequences exceeds 2LS, where $L = \#$ of letters in word and $S = \#$ of sequences shown before a letter is chosen

**User Feedback: Workload**

<table>
<thead>
<tr>
<th>Question</th>
<th>PLIS Avg Response</th>
<th>PLIS Range</th>
<th>Control Avg Response</th>
<th>Control Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>How much physical effort or activity was required to operate the system?</td>
<td>2.4</td>
<td>1-2</td>
<td>1.3</td>
<td>1-2</td>
</tr>
<tr>
<td>How much mental effort or activity was required to operate the system?</td>
<td>5.2</td>
<td>4-7</td>
<td>5.7</td>
<td>4-7</td>
</tr>
<tr>
<td>How much time pressure did you feel under?</td>
<td>2.5</td>
<td>1-6</td>
<td>4.0</td>
<td>1-6</td>
</tr>
<tr>
<td>What level of frustration did you experience?</td>
<td>3.5</td>
<td>1-7</td>
<td>2.5</td>
<td>1-5</td>
</tr>
<tr>
<td>Overall, how hard did you have to work during the task?</td>
<td>3.4</td>
<td>2-6</td>
<td>4.5</td>
<td>2-6</td>
</tr>
</tbody>
</table>


**Mastery Task Results (N = 17)**

<table>
<thead>
<tr>
<th>Mastery Task Level</th>
<th>N (PLIS/FLIS)</th>
<th>Avg. Prob of Success (PLIS)</th>
<th>N (Controls)</th>
<th>Avg. Prob of Success (Controls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>.25</td>
<td>11</td>
<td>.73</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>.53</td>
<td>10</td>
<td>.74</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>.89</td>
<td>7</td>
<td>.86</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.00</td>
<td>6</td>
<td>.80</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1.00</td>
<td>6</td>
<td>.80</td>
</tr>
</tbody>
</table>

* N = number of participants who successfully completed a given level (out of 6 for PLIS and 11 for controls)*

*Avg. Probability of Success determined by calibration results

**User Feedback: Comfort**

<table>
<thead>
<tr>
<th>Question</th>
<th>Participant Avg Response</th>
<th>Participant Range</th>
<th>Control Avg Response</th>
<th>Control Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>After using the system, do you have headache/ pain of any kind?</td>
<td>1.2</td>
<td>1-3</td>
<td>1.3</td>
<td>1-1</td>
</tr>
<tr>
<td>After using the system, do you feel tired, stranded or saturated?</td>
<td>2.0</td>
<td>1-5</td>
<td>2.5</td>
<td>1-5</td>
</tr>
<tr>
<td>After using the system, do you feel your neck/limb is uncomfortable?</td>
<td>1.4</td>
<td>1-4</td>
<td>2.5</td>
<td>1-3</td>
</tr>
<tr>
<td>After using the system, do your facial muscles feel tired, strained or painful?</td>
<td>2.2</td>
<td>1-5</td>
<td>2.5</td>
<td>1-4</td>
</tr>
<tr>
<td>Overall, did using the system make you comfortable or uncomfortable?</td>
<td>3.2</td>
<td>2-5</td>
<td>3.3</td>
<td>1-5</td>
</tr>
</tbody>
</table>

**User Feedback: Ease of Use and Overall Satisfaction**

<table>
<thead>
<tr>
<th>Question</th>
<th>Participant Avg Response</th>
<th>Participant Range</th>
<th>Control Avg Response</th>
<th>Control Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Did you find that letter selection was accurate or inaccurate?</td>
<td>3.1</td>
<td>1-6</td>
<td>2.2</td>
<td>1-5</td>
</tr>
<tr>
<td>Did you find that the speed of letter selection was fast or slow?</td>
<td>3.6</td>
<td>1-5</td>
<td>4.0</td>
<td>2-5</td>
</tr>
<tr>
<td>How satisfied are you with the system overall?</td>
<td>2.6</td>
<td>1-6</td>
<td>2.7</td>
<td>1-4</td>
</tr>
</tbody>
</table>

**Participant Profiles**

<table>
<thead>
<tr>
<th>Response</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Extremely satisfied</td>
</tr>
<tr>
<td>6</td>
<td>Considerably satisfied</td>
</tr>
<tr>
<td>5</td>
<td>Somewhat satisfied</td>
</tr>
<tr>
<td>4</td>
<td>Neither nor satisfied</td>
</tr>
<tr>
<td>3</td>
<td>Somewhat unsatisfied</td>
</tr>
<tr>
<td>2</td>
<td>Considerably unsatisfied</td>
</tr>
<tr>
<td>1</td>
<td>Extremely unsatisfied</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Response</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
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</tr>
<tr>
<td>6</td>
<td>Considerably comfortable</td>
</tr>
<tr>
<td>5</td>
<td>Somewhat uncomfortable</td>
</tr>
<tr>
<td>4</td>
<td>Neither nor comfortable</td>
</tr>
<tr>
<td>3</td>
<td>Somewhat satisfied</td>
</tr>
<tr>
<td>2</td>
<td>Considerably unsatisfied</td>
</tr>
<tr>
<td>1</td>
<td>Extremely unsatisfied</td>
</tr>
</tbody>
</table>

Fried-Oken, et. Al
RSVP Keyboard™: BCI for Users who have Locked-In Syndrome

ISAAC 2012
Pittsburgh, PA
Participant Profile: CG

- 65 year old woman
- Diagnosed with ALS in 2006, on vent since 2011
- Functional LIS (reliable eye movement + some reliable body movement)
- Scored 90% or above on all screening tasks
- Communicates via mouthing words, yes/no signals, SGD with foot-controlled trackball, or tracing letters with toe
- Seated in power wheelchair with comfortable, stable positioning
- Cap secured with chin strap (outside cervical collar)

Participant Profile: RJ

- 40 year old man
- Diagnosed with ALS in 2007, on vent since 2009
- Incomplete LIS (reliable eye movement)
- Scored 100% on all screening tasks
- Communicates via yes/no signals, eye-controlled SGD, or partner-assisted scanning
- Seated in power wheelchair with comfortable, stable positioning
- Cap secured with typical cap straps connected to chest strap

Participant Profile: PK

- 55 year old woman with spastic-athetoid CP
- Functional LIS (reliable eye movement + some body movement)
- Scored 100% on all screening tasks
- Communicates via keyboard-based SGD with stylus, yes/no signals, or partner-assisted scanning
- Frequent, uncontrolled movements when using RSVP Keyboard™
- Seated in manual wheelchair or lying in bed, all joints contracted
- Cap secured with sports headband over ears
RSVP Keyboard™: BCI for Users who have Locked-In Syndrome

Participant Profile: PK (cap secured with headband; support for head, upper back to reduce muscular tension)

Participant Profile: PK

Participant Profiles: Comparison

<table>
<thead>
<tr>
<th>PLIS</th>
<th># Calibration Attempts</th>
<th>Max Est. Probability of Success</th>
<th>Mastery Levels Completed</th>
<th>Overall Satisfaction with RSVP™ at last visit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG</td>
<td>13</td>
<td>1.00</td>
<td>5</td>
<td>1</td>
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<tr>
<td>RJ</td>
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<td>0.14</td>
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<td>5</td>
</tr>
<tr>
<td>PK</td>
<td>5</td>
<td>0.15</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Discussion

"It was so awesome to really be able to direct my thoughts and spell a word." CG

Challenges

Participant issues
- Bald head
- Physical Positioning
- Athetosis
- Level of alertness/arousal
- Decreased eye control
- Recent hospitalization/illness
- Medications
- Emotional stressors
- Fatigue/decreased concentration

Equipment issues
- Use of non-invasive wet electrodes
- SGD near computer
- Interference from equipment to manage complex medical conditions
- Lengthy set up time
Challenges

**Service Delivery**
- Training
- Ease of use
- Cost
- Portability
- Reliability
- Caregiver responsibility
- Technology support needs

**Next Steps**
- Customization for individual users
- Vigilance and attention measures
- Inclusion of personalized language models
- Stored calibration data over time
- Artifact reduction algorithms
- Patient-centered outcomes framework

Dear BCI Team,

I am so sorry to tell you, H passed away on Tuesday at noon.

I can’t tell you how much participating in this trial meant to him. It was probably more meaningful and life-preserving for him than his one ALS related drug said to extend his life maybe by 3 months. The BCI study gave him hope that there was a better world for locked-in patients to be in in the future. You guys are making the world a better place, you truly are.

My best,
Amie

“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