# Enhancing Brain-Machine Interface Throughput Using Simultaneous Activation Detection

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## Abstract
In this work, we investigate the viability of a novel combination of evoked responses as input signals for a general-purpose brain-machine interface (BMI). We demonstrate response accuracy to alphanumeric stimuli in valid and mirror-reversed orientations, and show task-related activity differences correlated with rotation degree and character validity in superior parietal and inferior frontal gyrus regions of the brain. By observing simultaneous task-related activation in spatially dissociated regions, we increase the amount of information used for inferring user intent in control interfaces.

## Keywords
Brain-machine interface, electroencephalography

## ACM Classification Keywords
J.4. Social and Behavioral Sciences (e.g., BMI): Miscellaneous.

## Introduction
A long-term objective of brain-machine interface (BMI) research is an interface sufficient for general-purpose control problems. A successful general purpose BMI

would detect stimulus related cortical activity using noninvasive sensor arrays in conjunction with signal inference methods to accurately infer user intent. Users would receive performance feedback that minimizes cognitive load and helps guide conscious control of cortical activity.

Traditionally, BMI has been applied to clinical assistive technology settings where spatially isolated cortical regions are used in temporally isolated tasks for signal detection [1]. In these studies, different mental tasks evoke signals in spatially different regions of the brain [2]. For instance, participants mentally add numbers to indicate a particular intent and imagine spelling words to indicate another. The goal of this work is to discover mental tasks that evoke near-simultaneous activation in spatially separate regions of the brain. The near-simultaneous activation of spatially separate regions allows more degrees of freedom for control signals and allows for application in continuous control settings. The work presented here demonstrates a novel combination of mental tasks resulting from the same stimulus that offers a richer, more usable set of control signals. ERPs to these tasks are constrained to relatively isolated cortical areas for detection. The benefits of this work extend the use of BMI outside of clinical settings while also enhancing the interface experience in assistive technology settings.

## Superior Parietal Lobe and Mental Rotation

Evoked response potentials in many regions of the brain have been well studied in the psychophysics community using electrical field, infrared spectroscopy, and blood-oxygen level responses [3-5]. This research has revealed that tasks requiring mental spatial manipulations (such as mental rotation) commonly evoke brain activity in and around the superior parietal lobe, especially in the right hemisphere [6]. There has been significant research on mental rotation tasks since Shepard and Metzler showed systematic differences in subject response time for similarity judgment correlated with the angle of rotation of a 3-dimensional object [7]. The Shepard-Metzler task is often used to evoke superior parietal lobe activation. Given two depictions of three-dimensional objects participants are asked to judge whether the objects are identical or not; the target is typically an enantiomer of the prime (see Figure 1). Initially revealed to result in primarily posterior activation [8], imaging studies show mental rotation is a right-lateralized function relying predominantly on structures in the parietal cortex [6]. Jordan and colleagues show lateralized parietal activation using fMRI [5].

## Language Production and Character Validity

Previous work with alphanumeric stimuli has shown differences in right superior parietal as well as

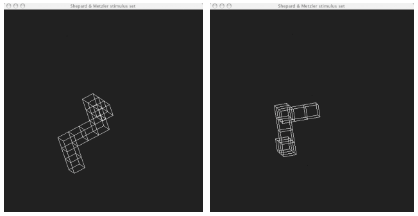

Figure 1. Example stimulus objects used in a previous pilot study measuring fNIR response differences in superior parietal regions; objects are recreated from the original images used by Shepard & Metzler 1971. In this study, the experimental task is to compare short animations of the object pairs in the original study for equivalence. The control task is a mental arithmetic task.

prefrontal activation when assessing character validity [10]. In these experiments, differences in superior right parietal activation were recorded when participants were shown rotated letters, whose upright orientation either was a valid character, or flipped about its central axis. While single trial information recorded over spatial memory is not sufficient for signal inference (noisy signals in conjunction with insufficient information in the signals), simultaneous activation in spatial memory and language production regions to these kinds of stimuli may provide sufficient information for signal inference.

By recording ERP in left hemisphere inferior frontal gyrus and right hemisphere superior parietal lobe, we believe we will capture sufficient information for inferring user intent using mirror-symmetric and rotational manipulations of letter stimuli. There is a spatial component in imagined manipulation of letters to upright as well as a language response to valid and invalid characters. Through the presentation of stimuli where both conditions are manipulated, we want to be able to recover the relative activation differences in superior parietal lobe and inferior frontal gyrus for rotation and character validity. Further, a discrete choice interface using rotation and character validity should be able to present many target stimuli at once (correlated with a target location or activity). Our experimental procedure captures these properties and tests participant ability to make these discriminations.

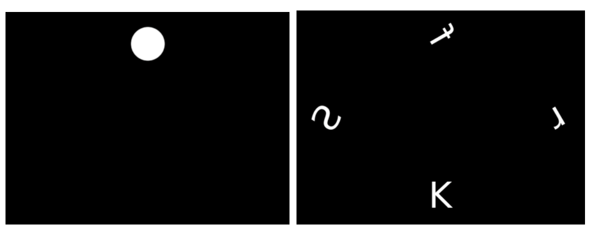


Figure 2. Example cue stimulus (left) shown for 300ms indicates the top location as the target of the following ordinal stimulus. Example ordinal stimulus (right) shows oriented letters at each ordinal location. In this case, the west and south characters are valid while the north and east characters are invalid (r,k,f,s respectively).

In a recent neuroimaging study of mental rotation, Milivojevic and colleagues noted task related activation in prefrontal regions of the brain [10]. Prefrontal activation has been noted in previous neuroimaging studies and attributed to attentional demands of the stimulus. Milivojevic and colleagues present evidence that for letter manipulations, rotation related activity is present in prefrontal regions. For the purpose of ERP related control using letter rotation based stimuli, we need to determine relative ERP differences in the inferior frontal gyrus and superior parietal regions for letter stimuli. The overall objective of the experiment presented here is to learn a discriminant function that maximizes inference of user intent, where participant attention is focused on stimuli to indicate intent. To test the viability of the combination of language production and spatial memory signals, we studied ERP of participants to stimuli of valid and invalid (flipped) alphanumeric characters.

## Experimental Setup

We recorded behavioral responses and ERP using EEG where task is to estimate if the upright figure was valid or not. Invalid characters consisted of backwards or mirror-symmetric characters (i.e. rotated 180 degrees about their central axis). Planar rotations were at 30-degree increments from 0 to 330 degrees. Participants used a keypress to indicate the behavioral response. Characters were placed at the four ordinal locations of the screen. Subjects were shown a cue prior to the stimulus window for 300ms, indicating which of the four stimuli to assess. The ordinal stimulus was shown for 600ms (see Figure 2).

## Experimental Methodology

3 subjects (1 female, mean age 23, all right handed) each completed 288 trials consisting of the ordinal stimuli. ERPs were recorded at 500Hz using 26 sensors arranged in the 10-20 system: Ft7, Fc3, Fcz, Fc4, Ft8, F7, F3, Fz, F4, F8, C3, Cz, C4, Cp3, Cpz, Cp4, C3, Cz, C4, P3, Pz, P4, Oz. Two reference electrodes on the left and right mastoids and four EOG electrodes were used. Participants were shown four practice trials prior to the experimental trials. Trial data were filtered for artifacts such as blink correction, band pass filtered, and trials were rejected for threshold activation.

## Results

Figure 3 shows correct and incorrect response counts for all participants for each stimulus condition. In the first graph, response data are shown for valid and invalid characters. Participants are more accurate for valid characters than invalid. The following graphs show response accuracy for each rotation angle for invalid and valid characters. Again, error rates are higher for invalid characters than valid characters for the same rotation angle. For invalid characters, error rates do not vary as a result of the rotational angle. For valid characters, errors are highest for 180-degree rotation. Further, there are few similarities in error rates for mirror angles to upright: 330-degree rotation error rate is lower than 30-degree rotation.

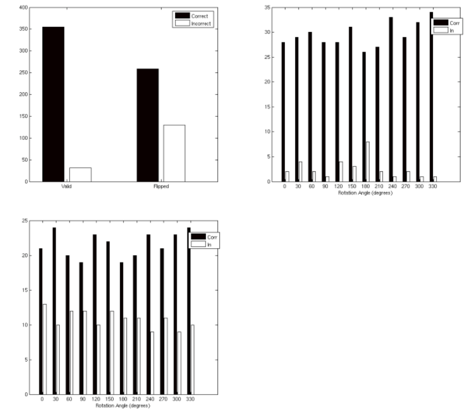

Figure 3. Response data aggregated by stimulus type for correct (black) and incorrect (white). The first graph shows responses for valid and flipped character types. The top right, bottom left graphs show response counts for valid and flipped character types by rotation angle.

*Valid/invalid Characters*

We averaged the trial time series of flipped and normal letter trials for each channel in the sensing array. For many channels, there was no significant difference in activation. The graph shows the averaged ERP for valid and invalid characters in Ft7. In this case, a positive amplitude difference exists starting at 200ms. This effect has been noted in prior ERP studies of the inferior frontal gyrus area (see Figure 4).

*Character Rotation*

We averaged trial time series for target characters with the same rotation angle. Again, for many channels in the array no significant difference in amplitude response was noted. In P4, amplitude differences in the latter time course indicate increased negativity as

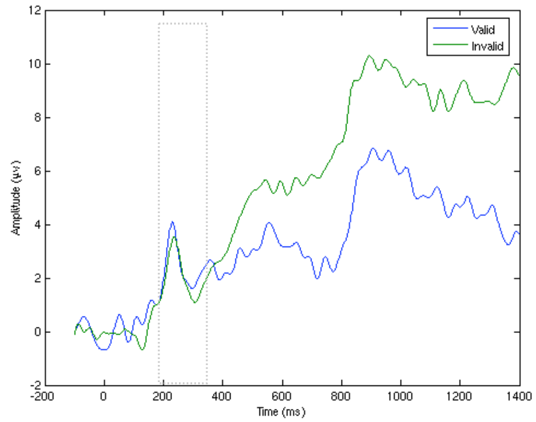


Figure 4. Averaged time series for channel Ft7 for valid (blue) and invalid (green) characters time-locked to the onset of the ordinal stimulus. In the early segment of the time course, a positive amplitude difference is tightly time correlated followed by a negativity difference (dashed line region). In the latter segment of the time course (400-500ms, 800-1000ms) amplitude differences indicate response differences to the stimuli

rotation angle increases. The negativity is consistent in the time course for different rotation angles (Figure 5).

## Discussion

The results presented here represent a pilot study of the feasibility of using mental tasks that simultaneously activate spatially separate regions of the brain for inferring user intent. The near simultaneous activation of the inferior frontal gyrus and the superior parietal lobe in response to the character stimuli is a novel combination of detectable activation differences from a single stimulus and provides a discriminable set of signals sufficient for control interfaces. The relative activation differences in response to increased rotational degree of stimuli provide one input from the letter stimuli. The results shown here indicate this response is detectable in the right superior parietal region. The activation response in the left inferior frontal gyrus is also detectable between the valid and mirror-reversed stimuli. The implications for use of mental rotation tasks in a discrete control interface setting are clear. In a discrete choice setting, manipulations of the letter stimuli may be arranged at target locations on the screen. Although we were able to show a response difference, this difference is less significant for continuous control purposes. The activation response of an invalid character is not easily extemporaneously generated, and therefore less useful as an added degree of freedom for control tasks. Other well understood phenomena such as steady state visual evoked responses (SSVEP) produce detectable activation differences in frequency space. For continuous control BMI, detecting activation from imagined tasks is a more desired outcome. We are interested in discovering tasks with simultaneous activation that are generative. The detectable activation difference over right superior parietal to the degree of rotation can be used in a continuous control task. In future work, we want to use other language production tasks associated with letter stimuli to generate response signals in left inferior frontal gyrus.

Finally, we have also noted similar detectable response differences in functional near-infrared spectroscopy data of the superior right parietal region when participants are asked to judge similarity when shown alternating animations of rotating objects (see Figure 1). The control task was a mental sequential arithmetic task. In this case, we found task related activation in superior right parietal, however the hemodynamic response did not show a response to rotation angle, in part due to the animation sequence used to evoke activation.

These initial pilot studies provide evidence that mental rotation tasks evoke signals sufficient for control tasks. Given these preliminary results, we expect a complete study combined with tasks that generate rather than evoke language production to yield a robust general purpose BMI. In particular, these preliminary results support discrete choice control settings.

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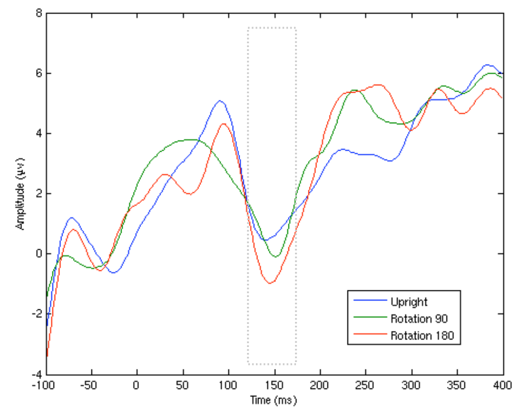


Figure 5. Averaged time series for channel P4 for characters rotated 0,90, and 180 degrees time locked to the onset of the ordinal stimulus. Over P4, amplitude differences show a negative amplitude response to increasing rotation degree of characters in the early segment of the time series

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