Defense-Related Insights and Solutions from Neuroscience and Neuroengineering

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ABSTRACT

Communication of intent usually requires motor function, which can be limiting during military missions. Determining a soldier's intent from brain signals rather than using muscles would have numerous applications for tactical combat. Brain-computer interfaces (BCIs) translate brain signals into machine readable form and could optimize a soldier's interaction with the surrounding environment. However, current BCI devices have largely remained laboratory curiosities, because current techniques either require extended training or do not have the requisite signal fidelity, because they are highly invasive and thus not safe or practical for use in humans, or because they rely on equipment (such as magnetic resonance imaging scanners) that do not allow for real-time applications and/or field deployment. The objective of our research program is to create a prototype of a system for communication and monitoring of orientation that uses brain signals to provide, in real time, an accurate assessment of the users intentional focus and imagined speech. We expect that our efforts will provide a prototype of the first intuitive brain-based communication and orientation system for human use.

Keywords: Brain-computer interface, electrocorticograpy (ECoG), directional orientation, attention, intention, silent communication, military applications

1. INTRODUCTION

Inquiring a soldier's directional orientation (e.g., direction of attention or intention) during combat is impractical, if not impossible, as it would require a motor response from the engaged soldier. This requirement is often limiting. Directly determining directional orientation from brain signals would have numerous applications for military use. For example, the locus of attention and/or intended movements could be used to optimize target acquisition or identification, thereby allowing soldiers to respond to and control the environment more rapidly and accurately. Moreover, translating brain signals into words and transmitting them wirelessly to radio speakers or earpieces would enable soldiers to communicate silently during a tactical mission. Brain-computer interfaces (BCIs) record signals from the brain and translate them into useful outputs.[1,2] Recent studies in the rapidly growing field of BCI research provide impressive demonstrations that BCI technology can allow people to communicate with others using brain signals alone.[3] However, current BCI devices do not readily support large-scale deployment largely because current techniques are either not practical for use in humans,[4] require extended user training,[5] or function only in particular environments.[6]

The objective of our research program is to establish the necessary methods and understanding that support creation of a prototype of a system for communication and monitoring of orientation. This system, in its finalized form, will use brain signals to provide, in real time, an accurate assessment of the users attentional focus, directional intent, and imagined speech. This objective is directly relevant to the mission of the Department of Defense (DoD) since these assessments could be used to improve or augment a soldier's performance and allow real-time silent communication. Its achievement requires that we identify brain signal features associated with these cognitive and behavioral functions, determine to which degree these features can be detected using non-invasive sensors, and finally create a system that can translate these features into a set of useful output functions

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in real-time. In this paper, we summarize our experiences in extracting neural correlates of attention, intention, and imagined speech from brain signals acquired from the surface of the brain (via a clinical methodology called electrocorticography (ECoG)), and manipulation of these extracted features for real-time computer control without the use of muscles. Future work includes advancing the real-time platform and determining whether similar features can be detected non-invasively.

2. METHODS AND MATERIALS

2.1 Data collection

Our approach to identifying brain signal features associated with the direction of attention, intention, and imagined speech involves recording of electrical brain signals invasively from the cortical surface of human subjects (ECoG) while they engage in behavioral tasks. These subjects are human patients that have electrode grids implanted on the surface of the brain for clinical reasons, mostly for the surgical treatment of intractable epilepsy.[7] All of our studies were approved by the Albany Medical College Institutional Review Boards, as well as by the Human Research Protections Office of the U.S. Army Medical Research and Materiel Command, and all subjects gave informed consent. We recorded ECoG signals at the bedside using eight 16-channel g.USBamp biosignal acquisition devices (g.tec, Graz, Austria) at a sampling rate of 1200 Hz or 9600 Hz. The implanted electrode grids (Ad-Tech Medical Corp., Racine, WI) consisted of platinum-iridium electrodes that were 4 mm in diameter (2.3 mm exposed), spaced at an inter-electrode distance of 1 cm, and were embedded in silicon. Electrode contacts distant from epileptic foci and areas of interest were used for reference and ground. The number of implanted electrodes varied between 64-112 contacts across subjects.

In addition to recording brain activity, we also recorded the subjects' eye gaze using a monitor with a built-in eye tracking system (Tobii Tech., Stockholm, Sweden), and the activity from peripheral devices such as a push button, joystick, headphones, and microphone. Data collection from the biosignal acquisition devices, stimulus presentation, and behavioral variables from peripheral devices, as well as control of the experimental paradigm, were accomplished simultaneously using BCI2000 software.[8, 9]

2.2 Feature extraction

Our analyses sought out to relate the brain signals to the parameters of interest related to the task (e.g., the direction of intended arm movements), and thereby to identify the brain signal features that are most predictive of certain parameters of the task. We also determined the relationship of the observed features across time and space to establish a mechanistic understanding of relevant cortical systems.

We began by first high-pass filtering all raw ECoG signals at 0.01 Hz and re-referencing signals from each electrode to a common average reference (CAR).[10] The CAR was computed separately for each 16-channel amplifier by computing the spatial mean across its input channels. For each 300 ms time period (stepping by 100 ms) and each location, we computed the power spectral density using an autoregressive model[11] of order 25 between 0.01 and 170 Hz in 1 Hz bins. We then averaged the spectral amplitudes in mu, beta and high gamma ranges (i.e., $8-12$ Hz, $18-26$ Hz, and $70-170$ Hz, respectively).

To study the ECoG correlates of behavior, we labeled the periods between trials as "baseline," and the periods during patients received instruction and performed a task as "behavioral engagement" (e.g.,"imagined speech"). We determined the correlation (Pearson's r) or coefficient of determination (r^2) between a particular spectral feature (e.g., gamma feature at a particular location) with the task, e.g., baseline versus attention. The significant features were used in classification between baseline and behavior, as well as in the classification of different experimental conditions as described below.

3. RESULTS FROM BEHAVIORAL PARADIGMS

3.1 Visual Attention

For attention and intention, our first goal has been to understand how a user orients to locations in space. To achieve this objective, we investigated the brain signals that capture the cognitive processes of attention and intention. Attention describes how sensory processing of specific spatial locations and object features is enhanced. Intention describes a specific motor representation that can be used to guide action, i.e., a movement plan. These processes are complementary. Attention governs how the brain processes sensory information, while intention is concerned with how that information is used to guide movements. Monitoring the spatial orientation of attention and intention will make possible a new generation of brain-based user interfaces that track and act on the focus of a user's orientation.

Our entry point to attention and intention has been to examine how orienting enhances the speed with which we can detect and respond to events that occur at the spatial locus of processing. Cognitive theories divide these operations into the process of attention that enhances sensory filtering, and the process of preparation to recruit a motor program. Both processes are critical for enhanced performance, but involve different neural computations. Therefore, we have executed a cueing experiment to distinguish and identify the brain networks for visual attention and motor preparation.

We find that frontal brain regions selectively respond to a visual stimulus when it is at the spatial locus of attention. Moment-by-moment, we can use brain signals to determine whether the subject is attending with an accuracy as high as 88.4% (50% chance), and the spatial locus of attention with an accuracy as high as 58.5% (33% chance) in five subjects.

3.2 Auditory Attention

To understand auditory attention, we executed dichotic experiments to identify the auditory stream (i.e., one of two speakers) and the location (i.e., left or right ear) a subject is attending to. When a subject is attending to one ear instead of the other, we find that signals in auditory regions of cortex rapidly indicate the correct spatial orientation that the subject attends to. Similarly, brain signals also correctly indicate the attended speaker. In fact, in this ongoing study, we can accurately decode both the ear and the speaker moment-by-moment from brain signals to give 91% correct identification of the ear and 81% correct identification of the speaker (50% chance each) in three subjects.

3.3 Intention

In the area of motor intention, we have executed experiments in which subjects move a cursor to different locations. We characterized the brain regions that correlate with hand movement intention and we have decoded the spatial locus of intention moment-by-moment. We find that brain signals encode both the intent (i.e., plan to move), as well as whether the subject is actually moving the hand. We can very accurately decode whether a subject intends to move (upto 93.3% accuracy, 50% chance in six subjects) and whether they are moving (upto 96.7% accuracy, 50% chance). Furthermore, in ongoing investigations, we find that brain signals also give substantial information about the direction of the intended and actual movements.

We have also generated initial evidence that the information described above may be used to improve performance in a targeting task. Once we decode where a subject intends to move, we position the cursor closer to their intended target. In offline simulations, this has improved the subjects' time to hit the target as high as 70% of the trials. In addition, we are currently building on and extending the understanding described above to work toward a real-time system that monitors spatial orientation moment-by-moment.

In summary, the studies described above build on two established domains in the cognitive neuroscience literature, which are related to spatial orientation for sensory attention and motor intention. Our results resolve with greater temporal precision than before how brain signals develop in subjects cued to orient the locus of processing to visual spatial locations, auditory streams, and hand movements. We show how we can track the flow of neural processing across occipital, parietal, frontal and temporal regions with very high temporal precision (i.e., tens of milliseconds). We are also able to resolve detailed information about the contents of the orienting process, such as the spatial locus of attention, the identity of a speaker, and the direction of hand movements. The performance we obtain is significantly more accurate than what has been previously obtained in human subjects. We also move significantly toward implementing our understanding in a real-time system and we are now well positioned to create a prototype system that will provide a real-time assessment of spatial orientation.

3.4 Overt and Covert Speech

For the speech studies, ECoG was recorded during word repetition using overt or covert speech in response to visual or auditory word stimuli. Visual and auditory stimuli consisted of 36 words that were presented on a video monitor or through headphones, respectively. These words were monosyllables with consonant-vowel-consonant structure and were either consonant matched (i.e., contained one of nine consonant pairs) or vowel matched (i.e., contained one of four vowels). In each trial, the subject was randomly presented with one of the words either visually or auditorily. In different runs, the subject's task was to repeat or imagine repeating the presented word. Using ECoG signals, we determined that it is possible to use these brain signal features to infer the vowel and consonant in the word that a person is speaking or even imagining (up to 58.7% accuracy; 25% chance accuracy in nine patients).

We further asked whether the brain signal features that were highlighted by the invasive recordings could also be derived non-invasively using scalp-recorded EEG. The results show for the first time that the time course of relevant EEG signals related to actual, but not imagined, speech are similar to those acquired using invasive recordings; and that these signals can be confidently ascribed to brain signal processes rather than concurrent muscular activity in the neck/throat. We then began to expand the current understanding of physiological phenomena related to speech. The results define for the first time a detailed relationship between different cortical regions during the speech process. In addition, we found – as another first – that brain signals in different parts of the gamma frequency band show differential information about different aspects of speech function. Finally, we asked whether the understanding achieved above would support an inference of speech-related imagery in single trials in online experiments. In particular, we examined the possibility that different elements of speech, in particular real and imagined articulation of phonemic sounds, can be accurately detected in real time. We demonstrated for the first time that brain signals can be effectively and accurately (i.e., up to 91% accuracy, 50% chance accuracy) used to select from one of two choices with minimal training.

4. CONCLUDING REMARKS AND FUTURE DIRECTIONS

Our research aims to create the necessary understanding and technologies to produce a minimally invasive and non-invasive BCI system that can derive information about directional attention, intention, and imagined speech in real time. We anticipate our findings will provide strong evidence that real-time interpretation of brain signals can reveal useful and previously inaccessible information about the current state of a human. To what extent this information can be extracted simultaneously, to what extent this information may be beneficial, and whether or not this information can be extracted in real time using procedures that can be operated by non-experts (as opposed to post-hoc analyses conducted by experts) is currently unclear. The objective for our future work is to answer these questions. Specifically, we plan to execute research to determine whether the different parameters identified above (e.g., attentional orientation and direction of intended movements) can be inferred simultaneously, the potential benefit of using brain signals in scenarios with Army relevance (e.g., whether brain signals can be used to decrease movement times in a targeting task), and whether it is possible to construct robust procedures (i.e., algorithms and procedures) that can be operated by non-experts and that can extract this information in real time.

Despite the significant accomplishments towards our objectives, it is currently unknown to what extent non-invasive scalp recordings encode parameters relating to directional attention and intention. At the same time, the results gathered from the minimally invasive ECoG data, which show that for the first time that the spatial location of attention and directional intention can be decoded in single-trials, are extremely encouraging and lay the foundation for the non-invasive studies.

Overall, we expect that our efforts will provide the understanding and procedures to support a prototype of a brain-based communication and orientation system for human use. The results will provide a significant step in transitioning BCI technology from laboratory demonstrations to important practical communication and augmentation applications. They should also contribute fundamental neuroscientific understanding in humans.

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