REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
06-10-2014	Final Report	4-Jun-2008 - 3-Jun-2014

4. TITLE AND SUBTITLE
Final Report: A Brain-Based Communication and Orientation Syatem

5a. CONTRACT NUMBER
W911NF-08-1-0216

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
54214-CS-MUR.33

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
This final report briefly reviews the objective and specific aims of this MURI project, then summarizes our progress toward these aims. The specific objective of this project, as stated in the application, was to develop 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 user's intentional focus, eye movements, and imagined speech." This project thereby sought to facilitate the DoD's mission by providing assessments that could eventually lead to improvements

15. SUBJECT TERMS
Final Report

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Gerwin Schalk
					19b. TELEPHONE NUMBER 518-486-2559

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

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ABSTRACT

This final report briefly reviews the objective and specific aims of this MURI project, then summarizes our progress toward these aims. The specific objective of this project, as stated in the application, was to develop 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 user’s intentional focus, eye movements, and imagined speech.” This project thereby sought to facilitate the DoD’s mission by providing assessments that could eventually lead to improvements or augmentations a soldier’s performance.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/24/2012	15.00	N. Jeremy Hill, Disha Gupta, Peter Brunner, Aysegul Gunduz, Matthew A. Adamo, Anthony Ritaccio, Gerwin Schalk. Recording Human Electrocorticographic (ECoG) Signals for Neuroscientific Research and Real-time Functional Cortical Mapping, Journal of Visualized Experiments, (06 2012): 0. doi: 10.3791/3993
08/24/2012	21.00	Eric C. Leuthardt, Gerwin Schalk. Brain-Computer Interfaces Using Electrocorticographic Signals, IEEE Reviews in Biomedical Engineering, (2011): 0. doi: 10.1109/RBME.2011.2172408
08/24/2012	20.00	Xiaomei Pei, J. Hill, G. Schalk. Silent Communication: Toward Using Brain Signals, IEEE Pulse, (01 2012): 0. doi: 10.1109/MPUL.2011.2175637
08/24/2012	19.00	Zuoguan Wang, Aysegul Gunduz, Peter Brunner, Anthony L. Ritaccio, Qiang Ji, Gerwin Schalk. Decoding onset and direction of movements using Electrocorticographic (ECoG) signals in humans, Frontiers in Neuroengineering, (2012): 0. doi: 10.3389/fneng.2012.00015
08/24/2012	18.00	Michael Tangermann, Klaus-Robert Müller, Ad Aertsen, Niels Birbaumer, Christoph Braun, Clemens Brunner, Robert Leeb, Carsten Mehring, Kai J. Miller, Gernot R. Müller-Putz, Guido Nolte, Gert Pfurtscheller, Hubert Preissl, Gerwin Schalk, Alois Schlögl, Carmen Vidaurre, Stephan Waldert, Benjamin Blankertz. Review of the BCI Competition IV, Frontiers in Neuroscience, (2012): 0. doi: 10.3389/fnins.2012.00055
08/24/2012	17.00	Eric C. Leuthardt, Xiao-Mei Pei, Jonathan Breshears, Charles Gaona, Mohit Sharma, Zac Freudenberg, Dennis Barbour, Gerwin Schalk. Temporal evolution of gamma activity in human cortex during an overt and covert word repetition task, Frontiers in Human Neuroscience, (2012): 0. doi: 10.3389/fnhum.2012.00099
08/24/2012	14.00	Cristhian Potes, Aysegul Gunduz, Peter Brunner, Gerwin Schalk. Dynamics of electrocorticographic (ECoG) activity in human temporal and frontal cortical areas during music listening, NeuroImage, (07 2012): 0. doi: 10.1016/j.neuroimage.2012.04.022
08/24/2012	13.00	Aysegul Gunduz, Peter Brunner, Amy Daitch, Eric C. Leuthardt, Anthony L. Ritaccio, Bijan Pesaran, Gerwin Schalk. Neural Correlates of Visual?Spatial Attention in Electrocorticographic Signals in Humans, Frontiers in Human Neuroscience, (2011): 0. doi: 10.3389/fnhum.2011.00089
08/24/2012	12.00	Dana Boatman-Reich, Peter Brunner, Mackenzie C. Cervenka, Andrew J. Cole, Nathan Crone, Robert Duckrow, Anna Korzeniewska, Anthony Ritaccio, Brian Litt, Kai J. Miller, Daniel W. Moran, Josef Parvizi, Jonathan Viventi, Justin Williams, Gerwin Schalk. Proceedings of the Second International Workshop on Advances in Electrocorticography, Epilepsy & Behavior, (12 2011): 0. doi: 10.1016/j.yebeh.2011.09.028
08/24/2012	16.00	Aysegul Gunduz, Peter Brunner, Amy Daitch, Eric C. Leuthardt, Anthony L. Ritaccio, Bijan Pesaran, Gerwin Schalk. Decoding covert spatial attention using electrocorticographic (ECoG) signals in humans, NeuroImage, (05 2012): 0. doi: 10.1016/j.neuroimage.2012.02.017
08/28/2011	2.00	Anthony Ritaccio, William Stacey, Mackenzie C. Cervenka, Nathan Crone, Peter Brunner, Christoph Guger, Eric Leuthardt, Robert Oostenveld, Gerwin Schalk. Proceedings of the First International Workshop on Advances in Electrocorticography, Epilepsy & Behavior, (11 2010): 0. doi: 10.1016/j.yebeh.2010.08.028

08/28/2011 10.00 C. M. Gaona, M. Sharma, Z. V. Freudenburg, J. D. Breshears, D. T. Bundy, J. Roland, D. L. Barbour, G. Schalk, E. C. Leuthardt. Nonuniform High-Gamma (60-500 Hz) Power Changes Dissociate Cognitive Task and Anatomy in Human Cortex,
Journal of Neuroscience, (02 2011): 2091. doi: 10.1523/JNEUROSCI.4722-10.2011

08/28/2011 11.00 L Bianchi, C Guger, F Cincotti, G Schalk, P Brunner. Current trends in hardware and software for brain–computer interfaces (BCIs),
Journal of Neural Engineering, (04 2011): 1. doi: 10.1088/1741-2560/8/2/025001

08/28/2011 9.00 Xiaomei Pei, Dennis L Barbour, Eric C Leuthardt, Gerwin Schalk. Decoding vowels and consonants in spoken and imagined words using electrocorticographic signals in humans,
Journal of Neural Engineering, (08 2011): 1. doi: 10.1088/1741-2560/8/4/046028

08/28/2011 8.00 Eric C Leuthardt, Charles Gaona, Mohit Sharma, Nicholas Szrama, Jarod Roland, Zac Freudenberg, Jamie Solis, Jonathan Breshears, Gerwin Schalk. Using the electrocorticographic speech network to control a brain–computer interface in humans,
Journal of Neural Engineering, (06 2011): 1. doi: 10.1088/1741-2560/8/3/036004

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Journal of Neural Engineering, (3 2011): 1. doi: 10.1080/10447318.2011.535748

08/28/2011 1.00 P Brunner, S Joshi, S Briskin, J R Wolpaw, H Bischof, G Schalk. Does the ‘P300’ speller depend on eye gaze?,
Journal of Neural Engineering, (10 2010): 1. doi: 10.1088/1741-2560/7/5/056013

08/28/2011 4.00 Peter Brunner, Anthony L. Ritaccio, Joseph F. Emrich, Horst Bischof, Gerwin Schalk. Rapid Communication with a “P300” Matrix Speller Using Electrocorticographic Signals (ECoG),
Frontiers in Neuroscience, (02 2011): 1. doi: 10.3389/fnins.2011.00005

08/28/2011 3.00 Eric C. Leuthardt, Charles M. Gaona, Peter Brunner, Jonathan R. Wolpaw, Gerwin Schalk, Xiaomei Pei. Spatiotemporal dynamics of electrocorticographic high gamma activity during overt and covert word repetition,
NeuroImage, (02 2011): 2960. doi: 10.1016/j.neuroimage.2010.10.029

08/30/2013 22.00 Anthony Ritaccio, Michael Beauchamp, Conrado Bosman, Peter Brunner, Edward Chang, Nathan Crone, Aysegul Gunduz, Disha Gupta, Robert Knight, Eric Leuthardt, Brian Litt, Daniel Moran, Jeffrey Ojemann, Josef Parvizi, Nick Ramsey, Jochem Rieger, Jonathan Viventi, Bradley Voytek, Justin Williams, Gerwin Schalk. Proceedings of the Third International Workshop on Advances in Electrocorticography,
Epilepsy & Behavior, (12 2012): 0. doi: 10.1016/j.yebeh.2012.09.016

08/30/2013 23.00 N. Jeremy Hill, Aisha Moinuddin, Ann-Katrin Häuser, Stephan Kienzle, Gerwin Schalk. Communication and Control by Listening: Toward Optimal Design of a Two-Class Auditory Streaming Brain-Computer Interface,
Frontiers in Neuroscience, (2012): 0. doi: 10.3389/fnins.2012.00181

08/30/2013 24.00 Nicholas R. Anderson, Tim Blakely, Gerwin Schalk, Eric C. Leuthardt, Daniel W. Moran. Electrocorticographic (ECoG) correlates of human arm movements,
Experimental Brain Research, (09 2012): 0. doi: 10.1007/s00221-012-3226-1

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NeuroImage, (12 2013): 0. doi: 10.1016/j.neuroimage.2013.06.085

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PLoS ONE, (1 2013): 0. doi: 10.1371/journal.pone.0053398

10/06/2014 32.00 Gerwin Schalk, Disha Gupta, N. Jeremy Hill, Matthew A. Adamo, Anthony Ritaccio. Localizing ECoG electrodes on the cortical anatomy without post-implantation imaging,
NeuroImage: Clinical, (2014): 0. doi: 10.1016/j.nicl.2014.07.015

10/06/2014 27.00 Emily P. Stephen, Kyle Q. Lepage, Uri T. Eden, Peter Brunner, Gerwin Schalk, Jonathan S. Brumberg, Frank H. Guenther, Mark A. Kramer. Assessing dynamics, spatial scale, and uncertainty in task-related brain network analyses,
Frontiers in Computational Neuroscience, (03 2014): 0. doi: 10.3389/fncom.2014.00031

10/06/2014 28.00 Ann-Katrin Häuser, Gerwin Schalk, N Jeremy Hill. A general method for assessing brain–computer interface performance and its limitations,
Journal of Neural Engineering, (04 2014): 0. doi: 10.1088/1741-2560/11/2/026018

10/06/2014 29.00 StÃ©phanie Martin, Peter Brunner, Chris Holdgraf, Hans-Jochen Heinze, Nathan E. Crone, Jochem Rieger, Gerwin Schalk, Robert T. Knight, Brian N. Pasley. Decoding spectrotemporal features of overt and covert speech from the human cortex,
Frontiers in Neuroengineering, (05 2014): 0. doi: 10.3389/fneng.2014.00014

10/06/2014 31.00 Disha Gupta, N Jeremy Hill, Peter Brunner, Aysegul Gunduz, Anthony L Ritaccio, Gerwin Schalk. Simultaneous real-time monitoring of multiple cortical systems,
Journal of Neural Engineering, (10 2014): 0. doi: 10.1088/1741-2560/11/5/056001

10/06/2014 30.00 Cristhian Potes, Peter Brunner, Aysegul Gunduz, Robert T. Knight, Gerwin Schalk. Spatial and temporal relationships of electrocorticographic alpha and gamma activity during auditory processing,
NeuroImage, (08 2014): 0. doi: 10.1016/j.neuroimage.2014.04.045

TOTAL: **30**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

"A General Method for Measurement of Brain-Computer Interface Performance and Its Limitations." Institute for Knowledge Discovery, Graz University of Technology, Graz, Austria, 09/17/2013.
"Sensorimotor Networks Detected in ECoG." BrainLinks-Brain Tools Seminar Series, School of Engineering, University of Freiburg, Freiburg, Germany, 09/19/2013.
"Brain-Computer Interfaces and their Future." Annual Conference of the International Bar Association, Boston, MA, 10/08/2013.
"Sensorimotor Networks Detected in ECoG." McGovern Institute for Brain Science, MIT, Cambridge, MA, 10/09/2013.
"Real-Time Functional Mapping Using Electrocorticographic Signals." Golby Lab, Harvard Medical School, Boston, MA, 10/10/2013.
"Sensorimotor Networks Detected in ECoG." 5th International Workshop on Advances in Electrocorticography, San Diego, CA, 11/08/2013.
"ECoG-Based BCI Systems." g.tec Brain-Computer Interface Workshop, Society for Neuroscience Annual Meeting, San Diego, CA, 11/09/2013.
"Real-Time Functional Mapping Using ECoG." g.tec ECoG/Spike Workshop, Society for Neuroscience Annual Meeting, San Diego, CA, 11/10/2013.
"Functional Mapping of the Human Brain." 4th Annual Meeting of the Minds Symposium, Charles B. Wang Center, Stony Brook University, Stony Brook, NY, 11/15/2013.
"The Exciting World of Brain-Computer Interfaces." Lecture in course Science in the News, Sage College, Albany, NY, 11/21/2013.
"Real-Time Functional Mapping Using Electrocorticographic Signals." Department of Neurosurgery, Virginia Commonwealth University, Richmond, VA, (from remote), 02/10/2014.
"Basic Tutorial: ECoG Neurophysiology." 6th Intl. Workshop on Advances in Electrocorticography, Berlin, Germany, 03/19/2014.
"Toward decoding of continuous spoken and imagined sentences from ECoG signals." 30th Intl. Congress of Clinical Neurophysiology (ICCN), Berlin, Germany, 03/20/2014.
"Basic and Applied Aspects of Adaptive Neurotechnologies." Department of Health Sciences and Research, Medical University of South Carolina, Charleston, SC, 04/09/2014.

Number of Presentations: 14.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

07/2014 g.tec BCI Award 2014 (our two submissions were nominated as finalists)
07/2014 World Technology Award (nominee in biotechnology)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Peter Brunner	0.50	
Emmanuel Morales	0.50	
Cristhian Potes	0.50	
Karen Dijkstra	0.50	
Rui Zhao	1.00	
FTE Equivalent:	**3.00**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Peter Brunner	0.30
FTE Equivalent:	**0.30**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Anthony Ritaccio	0.10	
Bijan Pesaran	0.05	
Aysegul Gunduz	0.25	
FTE Equivalent:	**0.40**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Peter Brunner
Cristhian Potes

Total Number: **2**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attached

Technology Transfer

Final Project Report

A Brain-Based Communication and Orientation System

PI: Gerwin Schalk, Ph.D.

54214-CI-MUR

Objective and Aims

This final report briefly reviews the objective and specific aims of this MURI project, then summarizes our progress toward these aims. The specific objective of this project, as stated in the application, was to develop 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 user's intentional focus, eye movements, and imagined speech." This project thereby sought to facilitate the DoD's mission by providing assessments that could eventually lead to improvements or augmentations a soldier's performance.

The three specific aims were:

1. **To delineate the brain signal features associated with the direction of attention, intention, and imagined speech.**

2. **To determine whether these features can be detected non-invasively.**

3. **To validate the use of brain signals for communication and orientation.**

Specific Aim One

We achieved substantial progress in delineating brain signal features associated with all three intended cognitive functions: direction of attention, intention, and imagined speech.

Attention

Our efforts to explore direction of intention included work with auditory and visual paradigms. In 2009, we began using ECoG to provide greater spatial resolution and more detailed information than noninvasive methods can provide. Five subjects performed a visual task with unpredictable changes in peripheral stimuli. We analyzed results with two goals: assessing key features reflecting neural correlates of attention; and assessing the efficacy of using ECoG to infer different aspects of attention (active attention vs. rest and different directions of attention). We first identified key parietal and prefrontal activities reflecting attentional processes, and showed a high classification accuracy with three of the five subjects. In 2010, we extended this work with additional research on visual spatial attention involving covert attention to cued stimuli. We again capitalized on the advantages of ECoG-based methods to provide new information about neural activity relating to attention, in visual, motor and prefrontal areas. We extended this work in 2011 with additional results showing classification of attentional activity well above chance. In 2012, we conducted additional studies exploring auditory and visual attention. For example, in one study, subjects listened to two speeches simultaneously – the inauguration speeches of Presidents Kennedy and Obama. We showed that we can distinguish which of these two binaurally presented conversations that a subject is attending. In 2013, we further explored data collected from our attentional research and found new ways to improve classification activity and understand some neural dynamics underlying attention.

Intention

Intention is linked to attention and orientation, and some of our early work in this project focused on intentional tasks relating to attention. In 2009, we collected data in which subjects performed a center-out task based on visual cues (circles that change color). We found that the optimal features needed to determine movement intent occur within 300 ms within the planned movement. We also began collecting data exploring intention and eye movements in a free-gazing paradigm. In 2010, further analyses of the center-out task and a similar study showed that we could distinguish left vs. right movement attention with very high accuracy, with new details about cortical activity in M1, premotor and parietal reach areas. We launched a major new study in 2011, with eight target locations and five experimental stages. ECoG data showed that we could predict movement intention prior to movement onset very well based largely on high gamma and LMP activity, and provided new insight about critical cortical regions. In 2012, in addition to further analysis of the data from 2011, we also we conducted two further studies regarding directional intention. These major efforts were extended through 2013. Based on linear regression and other means, we showed effective discrimination of movement vs. rest, as well as movement intent vs. rest. Further analyses also found additional new information about cortical regions involved in movement intention and the temporal dynamics of movement preparation and execution.

Imagined speech

In 2009, we reported that we collected EEG data from 16 subjects performing imagined speech tasks across five different studies. We extended these efforts in 2010 and found that ECoG was much more effective at decoding imagined speech than EEG. Hence, in 2011, we returned to ECoG-based research, collecting data from six subjects during covert and over speech tasks. We assessed spatial size and different high frequency bands. Interestingly, we found evidence suggesting different processes for overt vs. covert speech, and further found that early speech processing seems to differ if people intend either overt or covert speech. We extended this work in 2012 in the context of the well-established Indefrey model. Results with low-frequency and high-frequency data supported but also extended this model, and we conducted two more studies to further explore the time course of mental activity associated with imagined speech and identification of specific phonemes. In 2013, we reported new analyses of the speech envelope, with details of relevant cortical areas including the superior temporal gyrus and inferior frontal gyrus. We highlighted original electrophysiological evidence showing the speech envelope of non-auditory regions and their involvement in speech.

Specific Aim Two

Some of the research presented in the preceding section used ECoG methods. We recognize that these methods are less directly applicable to field applications. However, our work confirmed our expectations that ECoG-based research could provide helpful information that would improve non-invasive research. For example, we noted some improvements to our understanding of key cortical areas and processes, across different time scales, of planning and executing attentional, intentional and linguistic tasks. We compared results from EEG and ECoG recording with the same paradigm, such as in our 2009 comparison that found similar activation time courses in a language task.

In this Specific Aim, we stated that we would determine "whether these features can be detected noninvasively". Our ECoG work also helped identify avenues that are less promising for non-invasive work. For example, we concluded that EEG activity is relatively ineffective at imagined speech and analyses of complex movement planning, such as hand movement details. Some of our efforts in this Specific Aim were addressed through modeling efforts across different years. The efforts further supported our theoretical interests, with considerable synergy between the time course and general region of activity for both ECoG and EEG data, although EEG data were of course less detailed.

Specific Aim Three

We have indeed validated the use of brain signals for communication and orientation. We showed that ECoG (and sometimes also EEG) can indeed be used to learn about the user's auditory and visual attention, directional orientation, movement planning, imagined phonemes and other details. As noted in Specific Aim Two, we provided much more detailed information about which brain signals might be practical even with non-invasive means, and why. The aforementioned modeling efforts further bolstered our plans to develop intelligent real-time tools that can go well beyond conventional analyses by providing the system with a more thorough "understanding" of relevant brain states and processes.

Our efforts to validate brain signals for practical application were intertwined with our work with the BCI2000 software package. BCI2000 has been upgraded and improved in numerous ways over the past several years. Among other progress, we have added a newer and more flexible architecture, support for many more programming environments and third party software, integration of third party tools, improved documentation, additional software modules for new options, and improved capabilities for real-time processing under more challenging conditions (such as simultaneously recording two types of brain signals, or other inputs). BCI2000 is much better suited than other platforms when recording from a suite of biophysical signals, including activity from the brain, eyes, muscles, heart, respiration and other signals. BCI2000 has become the de-facto standard for real-time biosignal acquisition and analysis in BCI research, and is gaining attention in related fields.

In particular, BCI2000 has grown into a platform capable of clinical (as well as academic and commercial) research. BCI2000 has been very extensively validated in hospital environments with numerous patients, through the work in this MURI project and elsewhere. We remain very active in collaborations with clinicians in several countries who are using BCI2000 with patients, and feedback from end users continues to indicate that BCI2000 provides major advantages.

Collaboration and dissemination

The efforts in this MURI project involved substantial collaboration with top clinical and research experts. External collaborators during the project include Dr. Eric Leuthardt from the University of Washington, Dr. Christoph Guger from g.tec, Dr. Bijan Pesaran from New York University, and Dr. Kai Miller from Stanford University. We have ongoing collaborations with Dr. Cuntai Guan from the Institute for Infocomm Research in Singapore, Dr. Dean Krusienski from Old Dominion University, and Dr. Fabien Lotte from INRIA Bordeaux.

Results from this project have been published in high-impact peer-reviewed journals including NeuroImage, the Journal of Neuroscience, Frontiers in Neuroprosthetics, Frontiers in Human Neuroscience, PLoS One, Experimental Brain Research, and the Journal of Neural Engineering. In 2011, project work was selected as a finalist for the annual BCI Award, leading to a book chapter describing our work with Springer Publishing. In 2014, two different project-related studies were nominated as finalists (i.e., top ten of close to 100 submissions) for the annual BCI Award. We have also produced other book chapters with project results, along with dozens of conference presentations. We also disseminated the MURI project through several BCI2000 and ECoG workshops, which attracted students, doctors, engineers and other attendees.

Project results have also been disseminated in different ways by third parties who were not involved in this project. Our BCI2000 software has been used by hundreds of groups around the world, has been evaluated by the Army Research Laboratory in Aberdeen, and by investigators of the partner MURI (PI Dr. D'Zmura, Dr. Srinivasan). Several Workshop Tours conducted by g.tec (the top manufacturer of BCI hardware) have presented project achievements as promising uses of g.tec hardware. Project accomplishments were highlighted in the Future BNCI roadmap (commissioned by the EC) as examples of promising BCI research from the USA, and have been references in several peer-reviewed publications.

In summary, this section provides another means of verifying the success of our project – respect from peers. Our colleagues' respect for our achievements is reflected through numerous different means:

1) Prior and ongoing collaborations with top research groups;
2) Several peer-reviewed publications in top journals;
3) Dozens of citations of these publications;
4) Adoption of BCI2000 and other methods by different groups;
5) Participation in BCI2000 and ECoG workshops highlighting project results; and
6) Other dissemination of project accomplishments by third parties.

Conclusions

We have been very successful in attaining our aims, providing new insights into attention, directional orientation and imagined speech. While some challenges in developing practical, mainstream brain-based tools are still significant, we have made major progress toward this futuristic aim. We have soundly addressed previously daunting obstacles such as a truly practical, flexible real-time software system that can work with multimodal data and different devices. Our summary here does not at all detail our entire accomplishments in this project.

Our results will facilitate the direct assessment of a soldier's directional orientation, such as the locus of visual or auditory spatial attention or the direction of intended movements. These achievements will lead to new combat capabilities and applications. Our results with imagined speech should create new ways to communicate without any overt movement. The resulting novel communications opportunities, aside from tactical combat implications, could also benefit battlefield treatment and covert operations. This MURI project could also impact many related domains, including aviation, security, medicine and psychology. Moreover, we have developed new methods to analyze the brain, and provided new insights in neural function, that should continue to provide strong opportunities for future research.