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Research Paper

Flight simulation using a Brain-Computer Interface: A pilot, pilot study☆

Michael Kryger [a], Brock Wester [b], Eric A. Pohlmeyer [b], Matthew Rich [b], Brendan John [b], James Beaty [b], Michael McLoughlin [b], Michael Boninger [a,c,d,e,f], Elizabeth C. Tyler-Kabara [a,e,f,g,]*

[a] Department of Physical Medicine and Rehabilitation, University of Pittsburgh, Pittsburgh, PA, USA
[b] The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA
[c] Center for the Neural Basis of Cognition, Pittsburgh, PA, USA
[d] Department of Veterans Affairs Medical Center, Pittsburgh, PA, USA
[e] Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, USA
[f] McGowan Institute for Regenerative Medicine, University of Pittsburgh, Pittsburgh, PA, USA
[g] Department of Neurosurgery, University of Pittsburgh, Pittsburgh, PA, USA

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ABSTRACT

As Brain-Computer Interface (BCI) systems advance for uses such as robotic arm control it is postulated that the control paradigms could apply to other scenarios, such as control of video games, wheelchair movement or even flight. The purpose of this pilot study was to determine whether our BCI system, which involves decoding the signals of two 96-microelectrode arrays implanted into the motor cortex of a subject, could also be used to control an aircraft in a flight simulator environment.

The study involved six sessions in which various parameters were modified in order to achieve the best flight control, including plane type, view, control paradigm, gains, and limits. Successful flight was determined qualitatively by evaluating the subject's ability to perform requested maneuvers, maintain flight paths, and avoid control losses such as dives, spins and crashes.

By the end of the study, it was found that the subject could successfully control an aircraft. The subject could use both the jet and propeller plane with different views, adopting an intuitive control paradigm. From the subject's perspective, this was one of the most exciting and entertaining experiments she had performed in two years of research.

In conclusion, this study provides a proof-of-concept that traditional motor cortex signals combined with a decoding paradigm can be used to control systems besides a robotic arm for which the decoder was developed. Aside from possible functional benefits, it also shows the potential for a new recreational activity for individuals with disabilities who are able to master BCI control.

1. Introduction

The study of Brain-Computer Interfaces (BCIs) is expanding at a rapid pace (Brunner et al., 2015). This is, in part, made possible by various advancements in hardware and software, including data acquisition using neural interfaces and imaging modalities (Utah Array (Maynard et al., 1997)), sheer computing power to process signals in real-time, and improved functionality of rehabilitative technologies. BCIs have enabled users to interact with their environment, including exoskeletons (Kazerooni et al., 2005), anthropomorphic robotic arms such as the Johns Hopkins University Applied Physics Laboratory Modular Prosthetic Limb (MPL) (Johannes et al., 2011), and computer software used for communication, leisure, environmental control, and work productivity (Ebrahimi et al., 2003; Karmali et al., 2000; Krepki et al., 2007; Moore, 2003; Wolpaw et al., 2002).

Several surveys have explored the desired functional aspects of BCIs in patients with spinal cord injuries and motor neuron disease (Anderson, 2004; Blabe et al., 2015; Collinger et al., 2013a; Lahr et al., 2015). In a 2015 study, respondents rated their top four functions as: emergency communication, personal computer operation, robotic arms for self-feeding, and use of a power wheelchair for mobility (Huggins et al., 2015). In a survey conducted by our team, respondents

Abbreviations: BCI, Brain-Computer Interface; MPL, modular prosthetic limb; DARPA, Defense Advanced Research Projects Agency.

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* Corresponding author at: 4401 Penn Avenue, Floor 2, Pittsburgh, PA 15224, USA.
E-mail address: Elizabeth.Tyler-Kabara@chp.edu (E.C. Tyler-Kabara).

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with tetraplegia indicated that while bladder/bowel function was the most important aspect for restoring quality of life, arm/hand function, walking, and upper body/trunk strength were also very important goals (Collinger et al., 2013a). Huggins also asked similar questions of patients with Amyotrophic Lateral Sclerosis in 2011, who reported robotic arm use and motorized wheelchair control as important goals. Computer control was also desirable, but not as important. One case study of a 78 year old subject in a locked-in state found that a BCI system connected to a paint program provided a high degree of satisfaction and increased self-esteem. This subject ended up displaying her work at an art show (Holz et al., 2015). These surveys suggest that subjects seek to return to functional independence, especially when it involves use of an arm, mobility, and use of a computer.

BCI research has tended to focus on goals similar to those highlighted in these prior surveys, including robotic arm control, mobility devices such as exoskeletons, and computer use, both for games, communication and business (Ebrahimi et al., 2003; Krepki et al., 2007; Wolpaw et al., 2002). The authors' collaborative team, under the DARPA Revolutionizing Prosthetics Program (McLoughlin, 2009), implanted two intracortical electrodes in motor cortex of a subject. Cortical signs were used to progressively increase the complexity of control of the MPL. The subject ultimately achieved 10-dimensional control of the MPL to perform reaching and grasping movements (Collinger et al., 2014; Collinger et al., 2013b; Wodlinger et al., 2015).

Success in achieving independent real-time control opens the possibility that a BCI could allow an individual with paralysis to participate in other activities that require computer control. The goal of this study was to explore the ability of a participant to use a BCI to control a non-anthropomorphic device by piloting aircrafts using a flight simulator. This is primarily a proof-of-concept demonstration, starting with BCI control of only a few basic aspects of aircraft control.

2. Methods

2.1. Study participant

The study participant was a 53 year old woman diagnosed with a variant of spinocerebellar degeneration, without cerebellar involvement, resulting in complete quadriplegia (Boninger et al.). She was implanted with two 96-microelectrode arrays (Blackrock Microsystems, Salt Lake City, UT) in her left motor cortex (Collinger et al., 2013b). The series of trials described here were performed approximately two years post-implantation, over fifteen weeks. The study was conducted under an Investigational-Device Exception with FDA approval for the microelectrode array. The subject provided informed consent prior to participation in all research associated with this project.

2.2. Data acquisition

Neural signals were acquired from the intracortical microelectrode arrays using the NeuroPort Neural Signal Processor (Blackrock Microsystems, Salt Lake City, UT). Typically, the participant used her neural activity to control a prosthetic limb (MPL) (Collinger et al., 2014; Collinger et al., 2013b; Wodlinger et al., 2015). For these experiments, the existing MPL software and hardware communication interface control system (VulcanX) (Bishop et al., 2008; Ravitz et al., 2013) was utilized to transform velocity commands into control signals for the flight simulator. Neural firing rates were transformed into two dimensional velocity control signals for the MPL using a two-step calibration process as previously described (Collinger et al., 2013b). A neural decoder was built to control 2D endpoint velocity of the MPL. Typically, the participant controlled 2D translational velocity (up/down and left/right), although, we also tested rotational velocity (pitch and roll). During the first step of calibration, the participant watched the MPL move to targets in the appropriate workspace while she attempted to perform the movements herself. An initial neural decoder was built to relate neural firing rate to endpoint velocity. This decoder was used in a second step of calibration where the subject controlled the MPL using neural signals while the computer constrained the movements directly towards or away from the targets. A final neural decoder was built from this second calibration. This calibration was completed each testing day. While the relationships between imagined movement and directional control were used as the starting point of the aircraft control sessions, no effort was made to force the simulated aircraft to directly mimic limb motions. Instead, these mapping signals provided a starting point for the participant to learn how to work in 'plane space' and obtain effective direct control of the aircraft's control surfaces (Fig. 1). As a result, the participant had to use neural commands to learn how to effectively manipulate the control surfaces to achieve the desired aircraft responses. As the neural data was processed through VulcanX, there were additional parameters that provided extra limits and transformations of the data. These included (1) a threshold filter that excluded signals near zero to reduce noise, and (2) a transformation of the neural signal into scaled fractions of full deflections to reduce the overall complexity of control, and allow for faster changes in commands.

The neurally-commanded control surfaces included the elevators, used to control aircraft pitch (up and down movements of the aircraft nose), and the ailerons, used to control aircraft roll (rotation about the nose-to-tail axis of the aircraft). Control of the surfaces did not map in a 1:1 fashion to joint and endpoint movements of the prosthetic limb, as prosthetic limb control is velocity based (Clanton, 2011; Georgopoulos et al., 1986). For example, the velocities of the up and down wrist pitch were mapped to elevator positions. However, a neural command that caused the hand to pitch would not result in a constant nose up velocity of the aircraft. Instead, it resulted in positive deflection of the elevator that in turn caused the nose of the aircraft to pitch up at a greater than linear rate. Similarly, the neural command to rotate the limb wrist (pronation/supination) was mapped to the aileron positions. However, a neural command that caused a constant rotation of the limb hand had various impacts depending on the design of the aircraft. In the case of a jet aircraft that was tested (F-35), a constant aileron displacement caused a barrel roll of various speeds. In the case of the simpler propeller-driven aircraft (Mooney Bravo) that was tested, a constant wrist velocity command resulted in a turn of steadily decreasing radius. For either aircraft, changes in the positions of the ailerons impacted speed, which in turn affected how any given control surface position impacted the aircraft handling (i.e. a single control surface position does not have a fixed impact on the plane, but rather a variable one depending on the current speed and thus the previous commands/states in both control surfaces). While the subject was able to control aircraft heading as described above, she did not have control of acceleration during this process; instead, the aircraft was assigned a constant thrust.

2.3. Study sessions

This study involved six different sessions with varying parameters used to assess the participant's ability to control a simulated aircraft in flight. Parameters that were modified included airplane type (which impacted how the aircraft body responded to movements of the control surfaces/neural inputs), point of view (a first person pilot view or an 'out of body' external chase view), gains and thresholds related to converting commands from arm space to plane space, changes in environment and visual feedback (aircraft location, altitude, and accompanying scenery), as well as various task types (Table 1).

2.4. Data analysis

As an exploratory study, the data was evaluated qualitatively including data related to the participant's experience as described during the study sessions. The degree to which the study participant could control the aircraft was evaluated qualitatively based on how well she could