Getting the Message Across: Bridging ALS Communication Gaps with Brain-Machine Interfaces

Courtesy of UC Davis Health.

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Introduction

Communication remains a priority for people with speech disorders from neurologic conditions such as stroke and amyotrophic lateral sclerosis (Card et al., 2024). Amyotrophic lateral sclerosis (ALS) is a neurodegenerative condition that affects how the brain and spinal cord’s nerve cells communicate with muscles. This condition damages motor neurons that regulate voluntary muscle movements, causing symptoms of muscle weakness that progressively worsen and can lead to dysarthria, a motor speech disorder characterized by difficulty in forming and pronouncing words (“Amyotrophic Lateral Sclerosis,” n.d.; “Dysarthia,” n.d.). This lack of communication not only increases a diagnosed individual’s risk of isolation, depression, and decreased quality of life but also largely influences whether they pursue or withdraw from life-sustaining care in ALS (Katz et al., 1992; Lulé et al., 2009; Bach et al., 1993). While augmentative and assistive communication technologies like eye-tracking devices are available, these instruments experience low rates of information transfer and become increasingly difficult to use as patients lose voluntary muscle control with the progression of ALS symptoms (Fager et al., 2019). Ongoing efforts to develop speech neuroprostheses have culminated in a major breakthrough at the University of California Davis, where scientists have successfully created a novel device to translate brain activity into speech from an ALS patient (Card et al., 2024). This device possesses tremendous positive implications in the role of brain–machine interfaces and treatment strategies for irreversible neurologic conditions like ALS.

"Lou Gehrig's Disease"

Tackling novel treatment options requires an understanding of ALS. Cases of this disease can be divided into “sporadic” and “familial” types of ALS, with 90% of ALS diagnoses being sporadic—appearing randomly and not inherited from family members—and about 10% being caused by mutations from one or both biological parents during conception. Individuals are likely to develop symptoms for ALS between the ages of 55 and 75, with the condition most commonly affecting white, non-Hispanic people assigned male at birth (“Amyotrophic Lateral Sclerosis,” n.d.). Most famously, New York Yankees baseball player Lou Gehrig’s tragic battle against ALS left

behind a legacy of strength to future generations, and the condition was formerly called "Lou Gehrig's disease." Gehrig was committed to playing his beloved sport despite suffering from the disease until he was diagnosed in June 1939 and subsequently retired ("Lou Gehrig and the History of ALS," n.d.). Similarly to Gehrig, who passed away in 1941 at the young age of 37, people diagnosed with ALS experience mean survival times of approximately three to five years after diagnosis and this prognosis worsens rapidly as symptoms progress (Francis, n.d.; "Amyotrophic Lateral Sclerosis," n.d.). Moreover, the development of depression and anxiety due to the inability to communicate from complications with dysarthria further exacerbates this tragic outlook ("Amyotrophic Lateral Sclerosis," n.d.).

Dysarthria

Dysarthria is caused by damage to the brain via stroke, brain tumor, or other acquired brain injuries. The manifestations of the motor speech disorder vary based on the location of the damaged neurons within the brain. Flaccid dysarthria, for example, results from lower motor system damage and causes breathy and nasally speech. Contrastingly, spastic dysarthria is caused by damage to upper neurons in the brain and leads to strained or harsh tones in speech. Yet, all types of dysarthria negatively impact muscles with speech functions, preventing full control over body parts that control speech and resulting in speech that is difficult to understand. Despite the potential for possible improvement in communication through speech therapy, dysarthria remains largely irreversible due to its relation to chronic neuromuscular conditions, neurological trauma, strokes, and irreversible diseases like ALS. Notably, up to 30% of individuals diagnosed with ALS have dysarthria ("Dysarthia," n.d.). The lack of adequate and effective treatment has encouraged researchers to uncover more possibilities and strategies for rehabilitation, particularly using brain–machine interfaces.

Existing Literature

In ongoing efforts to develop speech neuroprostheses, a useful resource for comparison is provided by the many studies that analyzed the speech of able-bodied speakers under electrophysiological monitoring in clinical settings. In addition to this valuable wealth of data, successful cases of brain–computer interfaces being utilized in real-time to restore lost speech with implanted electrocorticographic arrays or intracortical multielectrode arrays have further inspired this area of research (Moses et al., 2021; Metzger et al., 2022; Metzger et al., 2023; Luo et al., 2023). In particular, two recent studies of established "brain-to-text" speech performance inspired the researchers at UC Davis to begin their research and development of neural prostheses. In these studies, cortical neural signals generated during attempted speech were decoded into phonemes, the "building blocks of words" that allow researchers to assemble the neural signals into words or sentences (Card et al., 2024). With a median word error rate measured as the percentage of words that were incorrectly decoded, the studies reached an error word rate of 25.5 percent from a 1,024-word vocabulary and 23.8 percent from a 125,000-word vocabulary (Metzger et al., 2023; Willet et al., 2023).

Methods

The team enrolled Casey Harrell, a 45-year-old man with ALS whose symptoms had begun five years before the study (Yehya, 2024). At the time of enrollment, he was non-ambulatory—depending entirely on others for everyday functions such as transportation, dressing, eating, and hygiene—and experienced limited orofacial movement with mixed upper- and lower-motor neuron dysarthria. Harrell's speech was largely unintelligible as he communicated at a mean rate of 6.8 correct words per minute when speaking

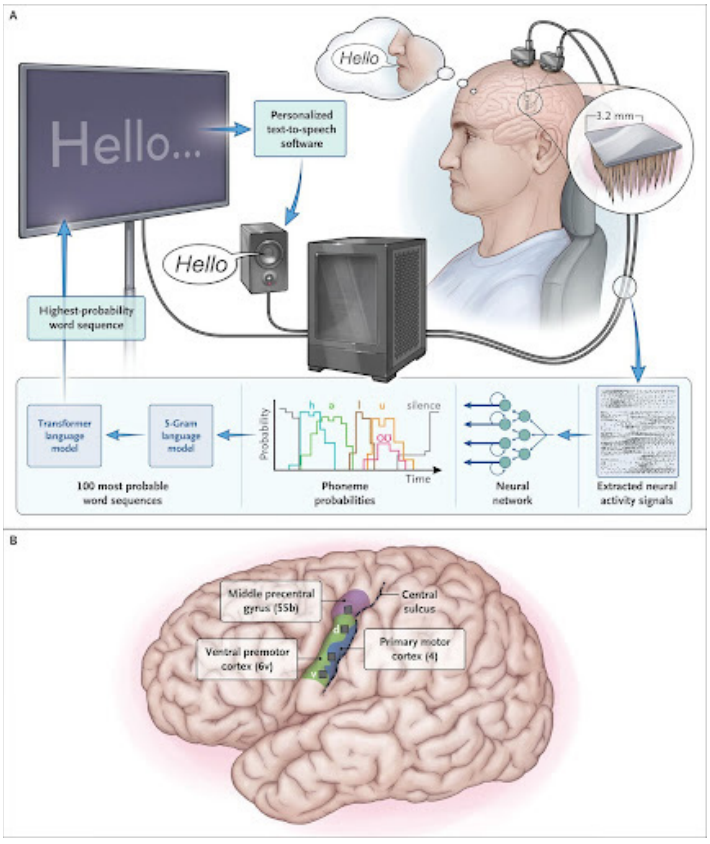

Figure 1. A diagram showing the locations of electrode and speech-decoding setup. Image courtesy of Card et al. (2024).

to expert listeners as compared to the rate of conversational English, which is approximately 160 words per minute. The severity of Harrell's dysarthria remained constant during the study period (Card et al., 2024).

The team of researchers implanted four microelectrode arrays into Harrell's left precentral gyrus, a cortical region necessary for the coordination of motor activities related to speech. The decision to target the speech motor cortex was informed by a previous study in which two arrays implanted in a participant's ventral premotor cortex provided informative signals for speech decoding (Card et al., 2024; Willet et al., 2023). Before implanting the microelectrode arrays, the researchers used functional MRI (fMRI) and standard clinical fMRI tasks like sentence completion, silent word generation, object naming, and others to confirm that the participant was left-hemisphere language dominant. Each microelectrode array was roughly 3.2 by 3.2 millimeters and was implanted through a five-by-five centimeter craniotomy on the left side under general anesthesia. Careful to avoid placing microelectrode arrays through large vessels on the cortical surface, the team inserted 664 electrodes in an eight-by-eight grid with each electrode designed to record signals from a small number of cortical neurons. Next, pedestals were secured to the skull with titanium screws for recording activity at 256 sites and then connected by detachable connectors that used HDMI cables to transmit data to computers. The researchers used signal-processing systems to acquire signals from the two connector pedestals that were sent to computers for real-time signal processing and decoding (**Fig. 1**) (Card et al., 2024).

Decoding Speech

Over 32 weeks and 84 sessions, the team collected data in Harrell's home. The participant used the implanted system in two ways: to complete an instructed-delay copy task, where words were shown on a computer screen and Harrell was asked to attempt to say the words after a visual or an audio cue, and in a participant-paced conversation mode that allowed him to participate in unstructured conversation. In both applications, cortical activity at four microelectrode arrays was recorded and decoded as the participant attempted to speak. As the sessions progressed, the team worked to calibrate the system to grow a more complex vocabulary and better adapt to Harrell's speech by predicting his words through neural networks. The neuroprosthesis was also able to punctuate sentences automatically and eventually send them to Harrell's personal computer similarly to a Bluetooth keyboard, allowing for activities like writing emails (**Fig. 2**) (Card et al., 2024).

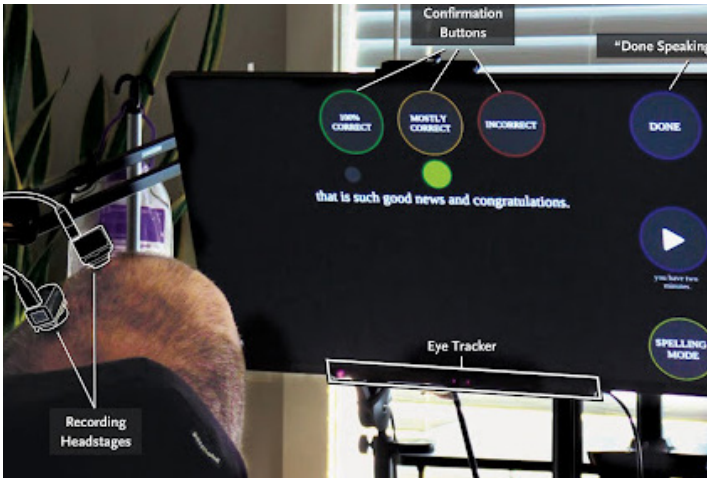

Figure 2. An image of the conversation-mode user interface. Image courtesy of Card et al. (2024).

Results

By the end of the study, the communication rate of the neuroprosthesis exceeded the participant's standard means of communication and could decode words with which it was not explicitly trained. Affirming a lack of acoustic or vibration-related contamination in the recorded neural signals, the researchers applied open-source language models to translate the predicted sequence of words into the most likely English sentence. In the first session, the team decoded Harrell's speech-induced cortical activity in real-time as the neuroprosthesis interpreted attempted speech with a word error rate of 0.44%, which served as an estimate of overall communication activity and was calculated as the ratio of the total number of words to the number of words expected to be decoded (**Fig. 3**). Errors were defined as any need for insertion, deletion, or substitution to match the decoded sentence to the intended sentence. Moreover, in the second research session, neuroprosthesis' expanded vocabulary from 50 to over 125,000 words, which encompasses most of the English language, allowed the participant to communicate freely. Within 16 hours of use, the neuroprosthesis incorrectly identified only 2.5 percent of attempted words (Card et al., 2024) in comparison to the five percent presented by most forms of advanced English automated speech recognition (Tüske et al., 2021). Furthermore, able-bodied speakers have a word error rate of approximately one to two percent when reading text aloud (Thomson et al., 2013). The participant in this study could converse at a rate of 32 words per minute, and the indicated that the system's voice even resembled his own. Upon completion of the study, the system decoded Harrell's attempted speech with an error rate of 9.8 percent—allowing the participant to use the conversation mode to fluidly perform activities ranging from talking to his research team, family, and friends to engaging in his occupation by participating in

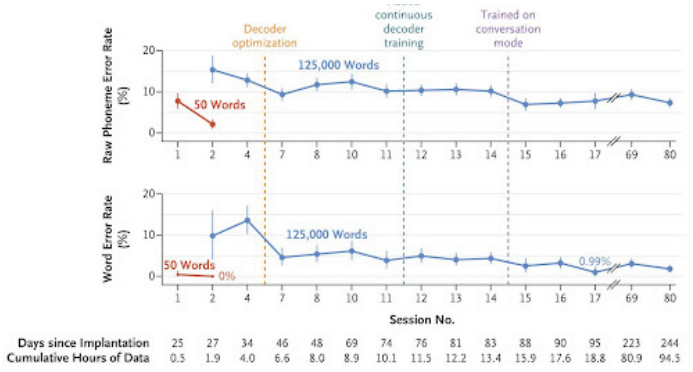

Figure 3. A graph displaying the improved performance of online speech decoding after the implantation. As shown in the graph, the neuroprosthesis was eventually able to decode the participant's attempted speech with a copy-task word error rate of 9.8% (Card et al., 2024).

videoconferencing meetings, writing documents, and more (Card et al., 2024).

Conclusions

While the development of this technology is radical in augmentative and assistive communication technologies, future investigation is necessary since the replication of similar results in future users with similar or different disorders is unknown (Card et al., 2024). Some limitations could include costs and access, as a surgical procedure is required for the neuroprosthesis. Also, since English serves as the foundation for most speech-to-text technologies, decoding other languages (e.g., Sino-Tibetan or Afroasiatic languages) could also present an obstacle due to the structural and lexical differences between language families. Yet, while expanding the vocabularies of brain–machine interfaces beyond the initial language of English would be more difficult, making this effort would be a commendable step towards ensuring more widespread access and inclusivity in globalized treatment plans. Overall, the study marks a significant accomplishment in restoring natural communication for individuals suffering from ALS. The profound accomplishment of this neuroprosthesis in achieving near-natural speech could drastically improve individuals' quality of life, as it may allow users to engage in real-time conversations with a regained sense of autonomy. Furthermore, the technological advancements of this study may encourage the development of advanced speech neuroprostheses that can decode more complex brain signals and ultimately benefit other conditions that also affect communication such as stroke or paralysis. More broadly, this innovative device may revolutionize and redefine approaches to disabilities, restoring lost functions through personalized and inclusive solutions with novel treatments tailored to the patient's needs.

References

"Amyotrophic Lateral Sclerosis (ALS)." Cleveland Clinic, my.clevelandclinic.org/health/diseases/16729-amyotrophic-lateral-sclerosis-als.

Bach, J R (1993). "Amyotrophic lateral sclerosis. Communication status and survival with ventilatory support." American journal of physical medicine & rehabilitation vol. 72,6: 343-9.

Card, N. S., Wairagkar, M., Iacobacci, C., Hou, X., Singer-Clark, T., Willett, F. R., Kunz, E. M., Fan, C., Nia, M. V., Deo, D. R., Srinivasan, A., Choi, E. Y., Glasser, M. F., Hochberg, L. R., Henderson, J. M., Shahlaie, K., Brandman, D. M., & Stavisky, S. D. (2024). "An Accurate and Rapidly Calibrating Speech Neuroprosthesis." The New England Journal of Medicine, vol. 391, no. 7, pp. 609-18, https://doi.org/10.1056/NEJMoa2314132.

"Dysarthria." Cleveland Clinic, my.clevelandclinic.org/health/diseases/17653-dysarthria.

Francis, Bill. "Lou Gehrig's legacy celebrated every day at Hall of Fame." National Baseball Hall of Fame, baseballhall.org/discover/lou-gehrigs-legacy-celebrated-every-day-at-hall-of-fame.

Fukushima, Makoto, et al (24 June 2014). "An electrocorticographic electrode array for simultaneous recording from medial, lateral, and intrasulcal surface of the cortex in macaque monkeys." Journal of Neuroscience Methods, vol. 233, pp. 155-65, https://doi.org/10.1016/j.jneumeth.2014.06.022.

Katz, R. T., Haig, A. J., Clark, B. B., & DiPaola, R. J. (1992). "Long-term survival, prognosis, and life-care planning for 29 patients with chronic locked-in syndrome." Archives of physical medicine and rehabilitation vol. 73,5: 403-8.

Koch Fager, S., Fried-Oken, M., Jakobs, T., & Beukelman, D. R. (2019). "New and emerging access technologies for adults with complex communication needs and severe motor impairments: State of the science." Augmentative and alternative communication (Baltimore, Md. : 1985) vol. 35,1: 13-25. doi:10.1080/07434618.2018.1556730.

"Lou Gehrig and the History of ALS." ALS Association, www.als.org/understanding-als/lou-gehrig.

Lulé, D et al (2009). "Life can be worth living in locked-in syndrome." Progress in brain research vol. 177: 339-51. doi:10.1016/S0079-6123(09)17723-3.

Luo, Shiyu et al (2023). "Stable Decoding from a Speech BCI Enables Control for an Individual with ALS without Recalibration for 3 Months." Advanced science (Weinheim, Baden-Wurttemberg, Germany) vol. 10,35: e2304853. doi:10.1002/advs.202304853.

Metzger, Sean L et al (2023). "A high-performance neuroprosthesis for speech decoding and avatar control." Nature vol. 620,7976: 1037-1046. doi:10.1038/s41586-023-06443-4.

Metzger, Sean L et al (8 Nov. 2022). "Generalizable spelling using a speech neuroprosthesis in an individual with severe limb and vocal paralysis." Nature communications vol. 13,1 6510. doi:10.1038/s41467-022-33611-3.

Moses, David A et al (2021). "Neuroprosthesis for Decoding Speech in a Paralyzed Person with Anarthria." The New England journal of medicine vol. 385,3: 217-227. doi:10.1056/NEJMoa2027540.

Thomson, D. R., Besner, D., & Smilek, D. (2013). "In pursuit of off-task thought: mind wandering-performance trade-offs while reading aloud and color naming." Frontiers in psychology vol. 4 360. 18 Jun. 2013, doi:10.3389/fpsyg.2013.00360.

Tüske Z, Saon G, Kingsbury B (3 May 2021). On the limit of English conversational speech recognition. (https://doi-org.ezp-prod1.hul.harvard.edu/10.48550/arXiv.2105.00982). preprint.

Willett, Francis R et al (2023). "A high-performance speech neuroprosthesis." Nature vol. 620,7976: 1031-1036. doi:10.1038/s41586-023-06377-x.

Yehya, Nadine (14 Aug. 2024). "Brain-Computer Interface Allows Man With ALS to 'Speak.'" UC Davis, www.ucdavis.edu/news/brain-computer-interface-allows-man-als-speak.