Comparing imagined handwriting BCI performance with other recent communication BCIs in people with paralysis

Krishna Shenoy, Stanford & HHMI, 4/8/21

1 Performance metrics: Typing Rate and Bit Rate

One BCI performance metric is typing rate, as described in [1], and is defined as:

$$T = \frac{S_c - S_i}{5t} \text{ wpm} \tag{1}$$

where T is typing rate in words per minute (wpm), S_c is the correct number of symbols (keys) transmitted including spaces and deletes, S_i is the incorrect symbols (keys) transmitted (which could then be deleted if there is a delete key), and t the elapsed time. We assume 5 characters (including spaces) per word on average. Note that this measure is does not leverage information-theoretic possibilities (e.g., see supplementary materials in [2], including channel coding).

Another BCI performance metric is achieved bit rate (i.e., the information throughput of the system under a single-symbol channel code), as described in [3]. In a single-symbol channel coded keyboard, the delete key is used to correct errors one symbol or letter at a time. Achieved bit rate is defined as:

$$B = \frac{log_2(N-1) \times max(S_c - S_i, 0)}{t} \text{ bps} \tag{2}$$

where B is the achieved bit rate in bits per second (bps), N is the number of selectable symbols on the interface (including delete key) and the -1 is because one key is the delete key. As in Eqn. 1, S_c is the correct number of symbols, S_i is the number of incorrect symbols and t is the elapsed time. The max function prevents bit rate from potentially being negative, which is not realistic.

2 Performance of the new attempted-handwriting BCI

The brain-to-text communication achieved via imagined handwriting study reported (1) an average of 90 characters / minute selection rate, (2) with a 5% error rate and (3) using a 31 symbol set size (26 lower case letters and a comma, apostrophe, question mark, period (written as '$\sim$') and spaces (written as '$>$'). This results in a T and B of:

$$T = \frac{S_c - S_i}{5t} = \frac{(90-4.5)-4.5}{5 \times 1} = 16.2 \text{ wpm} \tag{3}$$

$$B = \frac{log_2(N-1)max(S_c - S_i, 0)}{t} = \frac{log_2(30) \times max((90-4.5)-4.5, 0)}{60} = \frac{4.90 \times 81.0}{60} = 6.6 \text{ bps} \tag{4}$$

3 Attempted handwriting and point-and-click 2D cursor BCI performance

First, let's compare the handwriting typing rate of 16.2 wpm with our 2D cursor point-and-click result of (39.2 correct characters per minute) / (5 characters per word) = 7.84 wpm. This record was set by the same participant (T5) and employed the "OPTI-II" path-minimizing keyboard (Table 1, [4]). This is an improvement of 16.2 wpm / 7.84 wpm = **2.1**×.

Second, let's compare the handwriting bit rate of 6.6 bps with our 2D cursor point-and-click result of 4.2 bps, which was measured with a quasi-optimal density grid task which had 9 × 9 = 81 targets (Table 1, [4]). This is an improvement of 6.6 wpm / 4.2 wpm = **1.57**×.

Finally, it is important to compare performance in an apples-to-apples manner by employing keyboards with a similar number of keys. Our handwriting keyboard had 31 keys. In our previous 2D cursor point-and-click study [4] we also used task with 6 × 6 = 36 targets (Fig. 3b, [4]). In this task the bit rate was 3.7 bps. This is an improvement of 6.6 wpm / 3.7 wpm = **1.78**×.

4 Comparing communication BCI performance in people with paralysis

Table 1 below is a survey of BCI studies that measure typing rates (correct characters per minute; ccpm), bit rates (bps) and information transfer rates (bps) in people with paralysis. Table 1 below is the same as Table 1 from [4], with the addition of the top row to incorporate data from Willet and colleagues 2021 [5]. Number ranges represent performance measurements across all participants for a given study. Communication rates could be further increased by external algorithms such as word prediction or completion. As there are many such algorithms, our research [5, 4] excluded word prediction, word completion and automatic spell checking in order to focus on measuring the fundamental performance of the underlying system. The most appropriate points of comparison, when available, are bit rates, which are independent of word prediction or word completion algorithms. Similarly, information transfer rate (ITR) is also a meaningful point of comparison, though it is less reflective of practical communication rates than bit rate since bit rate takes into account the need to correct errors as detailed in [3, 6].

As shown, text generation performance with the new "attempted handwriting and RNN decoder" approach [5] exceeds all previous communication BCIs tested in people with paralysis. This includes our own previous record that employs a point-and-click 2D cursor operating on an on-screen keyboard [4]. ⊕These numbers represent performance when measured using a denser grid (9×9; Fig. 3, Fig. supplement 2 and Video 10 in [4]). ⊙For this study, reported typing rates included word prediction / completion algorithms. ♣Number range represents the range of performance reported for the single study participant. ♠Other reported numbers included word prediction / completion algorithms. †Acronyms used: Intra – Intra-cortical; ReFIT-KF – Recalibrated Feedback Intention-Trained Kalman Filter; HMM – Hidden Markov Model; CLC – Closed-loop Calibration; LDA – Linear Discriminant Analysis; and RTI – Retrospective Target Inference. Abbreviations: Brainstem stroke (BS), Cerebral palsy (CP), Duchenne muscular dystrophy (DMD), Spinal cord injury (SCI).

Table 1. BCI studies with highest typing rates, bit rates and information transfer rates (ITR).

Study	Subjects	Rec.	Ctrl.	Disability	Avg. ccpm	Avg. bps	Avg. ITR bps
[5] Willett et al. 2021	**T5**	**Intra**	**RNN**	**SCI**	**85.5**	**6.6**	**~6.6**
[4] Pandarinath et al. 2017	Avg (N = 3)	Intra	ReFIT-KF +HMM†	ALS (2), SCI (1)	28.1	2.4	2.4
[4]	T6	"	"	ALS	31.6	2.2	2.2
[4]	T5	"	"	SCI	39.2	3.7	3.7
[4]	"	"	"	"	-	⊕4.2	⊕4.2
[4]	T7	"	No HMM	ALS	13.5	1.4	1.4
[7] Bacher et al. 2015	S3	Intra	CLC+LDA†	BS	9.4	-	-
[8] Jarosiewicz et al. 2015	Avg (N = 4)	Intra	RTI+LDA†	ALS (2), BS (2)	⊙n/a	0.59	-
[8]	T6	"	"	ALS	"	0.93	-
[8]	T7	"	"	ALS	"	0.64	-
[8]	S3	"	"	BS	"	0.58	-
[8]	T2	"	"	BS	"	0.19	-
[9] Nijboer et al.	N = 4	EEG	P300	ALS	1.5–4.1	-	0.08–0.32
[6] Townsend et al.	N = 3	EEG	P300	ALS	-	0.05–0.22	-
[10] Munsinger et al.	N = 3	EEG	P300	ALS	-	-	0.02–0.12
[11] Mugler et al.	N = 3	EEG	P300	ALS	-	-	0.07–0.08
[12] Pires et al.	N = 4	EEG	P300	ALS (2), CP (2)	-	-	0.24–0.32
[13] Pires et al.	N = 14	EEG	P300	ALS (7), CP (5), DMD (1), SCI (1)	-	-	0.05–0.43
[14] Sellers et al.	N = 1	EEG	P300	BS	♣0.31–0.93	-	-
[15] McCane et al.	N = 14	EEG	P300	ALS	-	-	0.19
[16] Mainsah et al.	N = 10	EEG	P300-DS†	ALS	-	-	0.01–0.60
[17] Vansteensel et al.	N = 1	ECoG	Lin. Class.	ALS	♠1.15	-	0.21

References

[1] P Nuyujukian, J C Kao, S I Ryu, and K V Shenoy. A nonhuman primate brain–computer typing interface. *Proceedings of the IEEE*, 105(1):66–72, 2017.

[2] Gopal Santhanam*, Stephen I Ryu*, Byron M Yu, Afsheen Afshar, and Krishna V Shenoy. A high-performance brain–computer interface. *Nature*, 442(7099):195–198, 1 July 2006.

[3] Paul Nuyujukian, Joline M Fan, Jonathan C Kao, Stephen I Ryu, and Krishna V Shenoy. A high-performance keyboard neural prosthesis enabled by task optimization. *IEEE Transactions in Biomedical Engineering*, 62(1):21–29, 2015.

[4] Chethan Pandarinath*, Paul Nuyujukian*, Christine H Blabe, Brittany L Sorice, Jad Saab, Francis R Willett, Leigh R Hochberg, Krishna V Shenoy**, and Jaimie M Henderson**. High performance communication by people with paralysis using an intracortical brain-computer interface. *eLife*, 6, 2017.

[5] Francis R Willett, Donald T Avansino, Leigh R Hochberg, Jaimie M Henderson**, and Krishna V Shenoy**. High-performance brain-to-text communication via imagined handwriting. *Nature, in press*, 2021.

[6] G Townsend, B K LaPallo, C B Boulay, D J Krusienski, G E Frye, C K Hauser, N E Schwartz, T M Vaughan, J R Wolpaw, and E W Sellers. A novel p300-based brain–computer interface stimulus presentation paradigm: Moving beyond rows and columns. *Clinical neurophysiology: official journal of the International Federation of Clinical Neurophysiology*, 121(7):1109–1120, 1 July 2010.

[7] Daniel Bacher, Beata Jarosiewicz, Nicolas Y Masse, Sergey D Stavisky, John D Simeral, Katherine Newell, Erin M Oakley, Sydney S Cash, Gerhard Friehs, and Leigh R Hochberg. Neural Point-and-Click communication by a person with incomplete Locked-In syndrome, 2015.

[8] Beata Jarosiewicz, Anish A Sarma, Daniel Bacher, Nicolas Y Masse, John D Simeral, Brittany Sorice, Erin M Oakley, Christine Blabe, Chethan Pandarinath, Vikash Gilja, Sydney S Cash, Emad N Eskandar, Gerhard Friehs, Jaimie M Henderson**, Krishna V Shenoy**, John P Donoghue, and Leigh R Hochberg. Virtual typing by people with tetraplegia using a self-calibrating intracortical brain-computer interface. *Science Translational Medicine*, 7(313):313ra179, 2015.

[9] F Nijboer, E W Sellers, J Mellinger, M A Jordan, T Matuz, A Furdea, S Halder, U Mochty, D J Krusienski, T M Vaughan, J R Wolpaw, N Birbaumer, and A Kübler. A p300-based brain–computer interface for people with amyotrophic lateral sclerosis. *Clinical neurophysiology: official journal of the International Federation of Clinical Neurophysiology*, 119(8):1909–1916, 1 August 2008.

[10] Jana I Münßinger, Sebastian Halder, Sonja C Kleih, Adrian Furdea, Valerio Raco, Adi Hösle, and Andrea Kübler. Brain painting: First evaluation of a new brain-computer interface application with ALS-patients and healthy volunteers. *Frontiers in neuroscience*, 4:182, 22 November 2010.

[11] Emily M Mugler, Carolin A Ruf, Sebastian Halder, Michael Bensch, and Andrea Kubler. Design and implementation of a p300-based brain-computer interface for controlling an internet browser. *IEEE transactions on neural systems and rehabilitation engineering: a publication of the IEEE Engineering in Medicine and Biology Society*, 18(6):599–609, December 2010.

[12] Gabriel Pires, Urbano Nunes, and Miguel Castelo-Branco. Statistical spatial filtering for a p300-based BCI: tests in able-bodied, and patients with cerebral palsy and amyotrophic lateral sclerosis. *Journal of neuroscience methods*, 195(2):270–281, 15 February 2011.

[13] Gabriel Pires, Urbano Nunes, and Miguel Castelo-Branco. Comparison of a row-column speller vs. a novel lateral single-character speller: assessment of BCI for severe motor disabled patients. *Clinical neurophysiology: official journal of the International Federation of Clinical Neurophysiology*, 123(6):1168–1181, June 2012.

[14] Eric W Sellers, David B Ryan, and Christopher K Hauser. Noninvasive brain-computer interface enables communication after brainstem stroke. *Science translational medicine*, 6(257):257re7, 8 October 2014.

[15] Lynn M McCane, Susan M Heckman, Dennis J McFarland, George Townsend, Joseph N Mak, Eric W Sellers, Debra Zeitlin, Laura M Tenteromano, Jonathan R Wolpaw, and Theresa M Vaughan. P300-based brain-computer interface (BCI) event-related potentials (ERPs): People with amyotrophic lateral sclerosis (ALS) vs. age-matched controls. *Clinical neurophysiology: official journal of the International Federation of Clinical Neurophysiology*, 126(11):2124–2131, November 2015.

[16] B O Mainsah, L M Collins, K A Colwell, E W Sellers, D B Ryan, K Caves, and C S Throckmorton. Increasing BCI communication rates with dynamic stopping towards more practical use: an ALS study. *Journal of neural engineering*, 12(1):016013, February 2015.

[17] Mariska J Vansteensel, Elmar G M Pels, Martin G Bleichner, Mariana P Branco, Timothy Denison, Zachary V Freudenburg, Peter Gosselaar, Sacha Leinders, Thomas H Ottens, Max A Van Den Boom, Peter C Van Rijen, Erik J Aarnoutse, and Nick F Ramsey. Fully implanted Brain-Computer interface in a Locked-In patient with ALS. *The New England journal of medicine*, 375(21):2060–2066, 24 November 2016.