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# Neural encoding and decoding of multidimensional handwriting movement

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*Introduction:* The handwriting-based brain-computer interfaces (BCIs) have showed remarkable performance in brain-to-text communication [1], but the capacity to decode intricate handwriting movements, such as trajectories, from brain signals is an area that remains largely unexplored. A significant challenge is the limited understanding of how the brain encodes the nuances of fine handwriting movements.

*Material, Methods and Results:* We recorded intracortical neural signals from a paralyzed patient during imaginary handwriting of complex Chinese characters (Fig.1A), from which we reconstructed the trajectories of the handwriting and delved into the neural encoding properties. We introduced an innovated decoding framework that accommodates both shape and temporal distortions between movement and neural activity, and reconstructed closely resembled and human-recognizable handwriting trajectories (average CC >0.75, Fig.1B). Utilizing a dynamic time warping approach, we achieved a recognition rate of up to 91.1% within a 1000-character database (Fig. 1C) [2]. Upon examining the neural encoding properties of handwriting, we discovered that the tuning properties of individual strokes aligned with classical motor directional tuning theories [3]. However, the neural encoding of cohesions—air connections between strokes—differed significantly from that of the strokes themselves. Given that the kinematics of handwriting were not available from our paralyzed subject, we recorded multidimensional handwriting movements from healthy subjects to serve as a template, which encompassed 3D velocity of the pen tip, pen grip strength, pen tip pressure on paper, and 8-channel electromyography (EMG) on the forearm (Fig. 1D). Using a neural encoding model, we found that these additional variables accounted for more variance in the neural signals, suggesting that the brain encodes handwriting in multiple dimensions rather than just 2D. When these additional dimensions were decoded and incorporated for handwriting trajectory recognition, the decoding performance could be significantly improved.

*Conclusion:* We demonstrated a new decoding scheme for BCIs that could accurately reconstruct the imaginary handwriting trajectory, which paves the way for a universal brain-to-text communication system that is translational to any written language. Moreover, our results indicated that the brain encodes handwriting as multidimensional movements, and by leveraging this, we can further enhance the decoding performance for handwriting-based BCIs.

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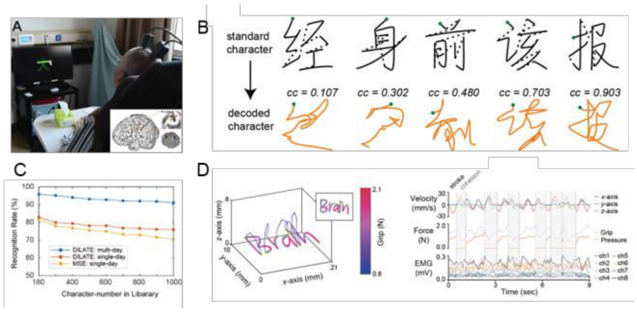


Figure 1: *A, Experimental setup. B, Example decoding trajectories for 5 Chinese characters. C, Recognition rate as a function of character number in the library. D, Multidimensional kinematic and kinetic traces for handwriting of the English word 'Brain'.*

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