Decoding Individual sequence skill learning actions during planning and execution

Debadatta Dash, Fumiaki Iwane, Roberto Salamanca-Giron, Marlene Bonstrup, Ethan Buch, Leonardo Cohen
HCPS, NINDS, NIH

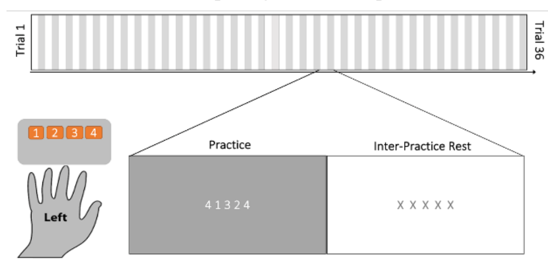
Background: Activities of daily living rely on our ability to learn new skills composed of precise action sequences. Deconstructing a sequence and decoding individual actions is challenging, since both the individual action and precise role of the action within the sequence are simultaneously represented by ongoing neural activity dynamics. Furthermore, while the representations of individual actions are known to be stationary, representation elements related to sequence structure are likely to evolve over time. This study attempts to address this problem by decoding the neural representation of sequence-dependent individual actions during skill learning for improved decoding performance. Accurate decoding performance is important in detection of neural replay events – important markers for investigating memory formation and consolidation – as well as in applications of rehabilitation-oriented brain-machine interfaces (BMIs).

Methods: We recorded magnetoencephalography (MEG) recordings of 26 participants while they learned to perform a novel motor skill (typing [4 (index) – 1 (little) – 3 (middle) -2 (ring) – 4 (index)]) with their non-dominant left hand over 36 trials of practice (10 s) interspersed with rest (10 s) (Fig.1). We trained machine learning decoders to classify individual finger movements from neural oscillatory activity measured in source space. We then evaluated the decoding performance for each trial and related to the trial-by-trial behavioral performance defined as correct sequence typing speed (skill). Additionally, we examined trial-by-trial changes in the neural representation of the same (index) finger movement at different ordinal positions of the sequence in relation to skill over rest (micro-offline: Between trials) and practice (micro-online: within trial) periods within the training session.

Results: Finger identities were successfully decoded preceding movement onset (~86% accuracy) and during movement execution (~90% accuracy). Low frequency oscillations (LFO, delta: 1-3 Hz and theta: 4-7 Hz) in superior frontal, pre- and post-central, and middle frontal regions contributed the most to decoding (Fig.2). Optimal decoding performance was obtained using a hybrid combination of whole brain parcels and the voxels of these motor networks. Decoding accuracy improved progressively tracking performance gains during early learning (initial 11 trials where performance reached to 95% of peak performance) and plateaued when performance stabilized during late learning (12- 36 trials). The neural representations of the index finger at different ordinal positions of the sequence differentiated progressively during early learning. This differentiated representation correlated strongly with skill gains (r = -0.868, R^2 = 0.753, $p < 0.001$) and developed predominantly over rest intervals. Furthermore, decoding ordinal positions of the sequence members (I.e., 5 class classification of 4-1-3-2-4) resulted in significantly higher accuracy (post: 94% and pre: 90% movement onset) compared to decoding the four finger identities.

Conclusion: This approach provides the most accurate strategy to date to decode individual actions from neural activity in the context of skill learning as required for identification of neural replay and optimization of control of BMI devices.

Fig. 1: Experimental Design



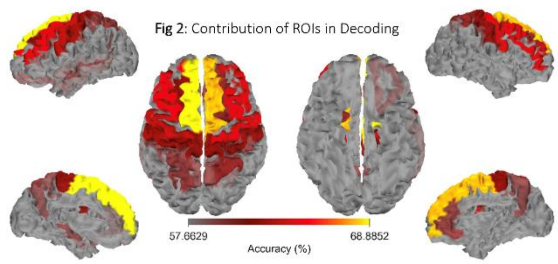


Fig 2: Contribution of ROIs in Decoding

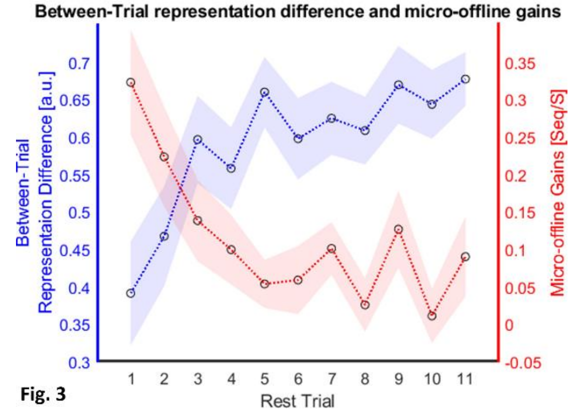


Fig. 3

Fig.4: Confusion Matrix: Execution
Accuracy = 94.15%; Weighted Mean F1 Score = 0.94
F1(Little) = 0.95; F1(Ring) = 0.94; F1(Middle) = 0.94; F1($Index_{OP1}$) = 0.94; F1($Index_{OP5}$) = 0.94