Neural subspaces for motor planning and execution in Parietal Cortex

S. Diomedi (stefanodiomedi@cnr.it)
Institute of Cognitive Sciences and Technologies, National Research Council, Padova, Italy

F.E. Vacari (francesco.vaccari6@unibo.it)
Dept. of Biomedical and Neuromotor Sciences, University of Bologna, Italy

K. Hadjidimitrakis (kon.chatzidimitrakis@unibo.it)
Dept. of Biomedical and Neuromotor Sciences, University of Bologna, Italy

P. Fattori (patrizia.fattori@unibo.it)
Dept. of Biomedical and Neuromotor Sciences, University of Bologna, Italy

I.P. Stoianov (ivilinpeev.stoianov@cnr.it)
Institute of Cognitive Sciences and Technologies, National Research Council, Padova, Italy

Abstract

Understanding how the brain plans and executes movements remains a major challenge in neuroscience. The superior parietal lobule (SPL), with its central role in sensorimotor integration and visuomotor transformations, is a key region in unraveling these mechanisms. We used dimensionality reduction techniques to investigate the structure of neural subspaces underlying latent dynamics during movement planning and execution in SPL. Specifically, we tested three alternative hypotheses about the relationship between subspaces in the two phases: (i) neural subspaces completely overlap between the two phases; (ii) planning and execution are characterized by independent activity patterns along orthogonal dimensions; and (iii) the dynamics are partially shared and partially exclusive. We analyzed population activity recorded from three SPL areas (V6A, PEc, PE) in macaques performing a delayed reaching task. Our results reveal that in areas V6A and PEc, shared neural patterns coexist with phase-specific subspaces, while in PE, the activity is organized along largely orthogonal subspaces. This distinction reflects the different sensorimotor processing roles of these regions and enhances our understanding of how parietal cortex contributes to motor control.

Keywords: Posterior Parietal Cortex · Movement Planning and Execution · Reaching Task · Neural Subspaces

Introduction

The posterior parietal cortex is crucial in motor control, integrating sensory inputs to guide actions through prediction and feedback. During planning, it encodes multiple context-based action intentions across modalities, while during execution, it estimates effector states using visual and proprioceptive feedback (Cui, 2014). The superior parietal lobule (SPL) is especially involved in planning and executing of reaching movements. Within the SPL, which shows a rostral-to-caudal gradient from somatosensory to visual dominance, three key areas emerge along this gradient: PE, PEc, and V6A (Figure 1a). PE receives primarily somatosensory input and is involved in multi-joint coordination, proprioception, and posture. It also encodes movement parameters such as depth and direction, but lacks visual input (Gamberini et al., 2020). In contrast, PEc and V6A are visuomotor areas, modulated by both visual and proprioceptive signals, and involved in encoding motor parameters for voluntary eye and arm movements (Gamberini et al., 2017). In the last decade, dimensionality reduction techniques have led to the neural state-space framework, a powerful method for analyzing large-scale neural activity during behavioral tasks. This approach shows that population activity occupies a low-dimensional neural subspace rather than the full high-dimensional space defined by all recorded neurons. Using this approach, researchers found that the motor cortex contains distinct, orthogonal subspaces for different motor phases (Kaufman et al., 2014). Elsayed et al. (2016) identified separate subspaces for preparation and execution, suggesting functional reorganization. Unlike in motor and premotor cortices, such functional reorganization is not clearly evident in the posterior parietal cortex (PPC), despite its involvement in diverse sensorimotor roles. This study provides the first characterization of neural subspaces in the SPL during movement preparation and execution. We investigate whether neural activity in these areas is organized into exclusive or exclusive and shared subspaces, shedding light on the structure of visuomotor and somatomotor representations in the parietal cortex.

Methods

In this study, neural activity from single neurons recorded in macaque areas V6A, PEc, and PE during an instructed-delay foveated reaching task in darkness was analyzed (10 trials performed for each of the 9 targets). The planning epoch (Plan) spanned 150–450 ms after fixation onset, and the movement epoch (Move) from 50 ms before to 250 ms after movement onset. Data were analyzed using the Pearson correlation coefficient and dimensionality reduction techniques: classical PCA to highlight phase-specific variance and an optimized PCA variant to identify orthogonal, exclusive and shared subspaces (where exclusive subspaces capture variance unique to a specific phase, shared subspaces represent variance common across multiple phases, and orthogonal subspaces ensure minimal overlap between phase-specific components) with normalized variance (Jiang et al., 2020) and linear regression quantifying variance capture and overlap across phases. In the results the following notation is used: explained self-variance refers to the amount of variance in the activity that is captured by the subspace that generated it. Conversely, explained cross-variance indicates the extent to which the same subspace accounts for the variance in neural activity that did not generate it.

Results

Neural correlations and PCA suggest independence Correlation matrices were computed for the planning and movement epochs in areas V6A, PEc, and PE to assess the stability of population activity patterns across task phases. The correlation structure observed during planning was largely disrupted during movement (see Figure 1b). To quantify this disruption, we computed the correlation between corresponding cross-correlation matrices across epochs. The resulting coefficients were low (R^2: V6A, 0.09; PEc, 0.03; PE, 0.02), This suggests that neural activity patterns differ between the two epochs. Furthermore, using PCA, a 10-dimensional subspace was extracted separately for the Planning and Movement epochs. Normalized cross-variance values (V6A: 0.30, PEc: 0.23, PE: 0.18) were low but above chance level (p-val¡0.05, one-tailed test), indicating partial orthogonality between the two epochs. The result in PE was particularly close to the chance distribution, suggesting more distinct subspaces in this area.

Orthogonal subspaces in somatomotor area PE Using Optimized PCA, we identified an Plan orthogonal subspace

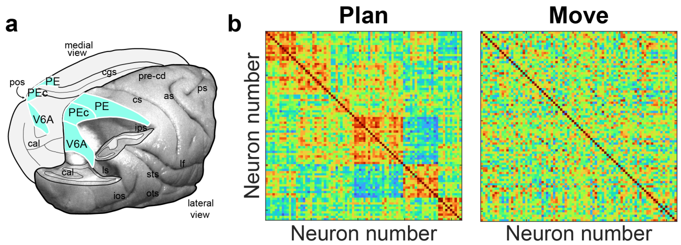

Figure 1: (a) Posterolateral view of macaque brain. The right hemisphere has been partially dissected at the level of the fundus of intraparietal, parieto-occipital, and lunate sulci to show the parieto-occipital sulcus. (b) Example of correlation matrices for the Plan and Move epochs for all neurons in PEc area. Each entry in the matrix represents the similarity between the response patterns of two neurons during the specified epoch. The order of neurons is the same for the Plan and Move epoch matrices.

that explained 93%, 98% and 97% and a Move orthogonal subspace that explained 93%, 97% and 97% of the self-variance in V6A, PEc and PE, respectively. This was further confirmed in the normalized cross-variance, which reached approximately 10% (Figure 2a). The critical question was whether this 10% explained cross-variance was merely attributable to noise or if there existed a meaningful relationship between the computations occurring in the two epochs. To investigate this issue, we employed linear regression to determine whether patterns in the Plan orthogonal subspace could predict patterns in the Move orthogonal subspace. As shown in Figure 2a), only in PE this prediction did not exceed chance level, confirming full orthogonality between planning and execution dynamics in this area. In contrast, significant predictive relationships were observed in PEc and V6A, suggesting the presence of shared components between the two phases.

Exclusive and shared subspaces in visuomotor areas V6A and PEc We identified both exclusive and shared subspaces for planning and movement. In V6A (PEc) the Plan exclusive subspace captured 74% (84%) of the normalized self-variance, while the Move exclusive subspace explained 76% (87%). The shared subspace accounted for 33% (30%) of the normalized preparation variance and 30% (24%) of the execution variance (Figure 2b).

Discussion

The study examined neural population dynamics in SPL during reaching tasks, focusing on the planning and execution phases. Using state-space frameworks, correlation analyses, and PCA, we found that each subspace captured most of the self-variance, while cross-variance remained minimal indicating that the underlying neural patterns for planning and execution are fundamentally different. However, the degree of separation varied across areas. PE shows orthogonal dynamics between planning and execution, likely to separate representations of planned body states from motor commands and sensory feedback, enabling precise and adaptive motor control. V6A and PEc display both exclusive and shared subspaces, suggesting integration of motor intentions and sensory feedback, with the shared subspace possibly reflecting stable eye position signals and persistent target representation. These differences across rostral and caudal PPC can also be interpreted within a state estimation framework (Medendorp & Heed, 2019): PE encodes dynamic body-related changes, while V6A and PEc maintain a stable representation of the external environment. Overall, the findings support an antero-posterior organization within the posterior parietal cortex, with a shift from shared dynamics in caudal areas (V6A and PEc) to more independent motor-like processing in the rostral area (PE).

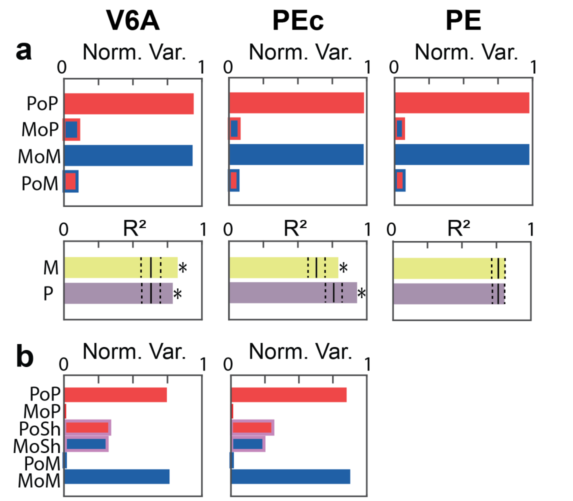

Figure 2: (a) Orthogonal subspaces normalized Variance and linear estimation. Yellow bar: R^2 of the linear estimation of Move dynamics in the Move subspace from the Plan projected its subspace; Pink bar: the opposite. Asterisks indicate significant differences from the null distribution (dashed lines). (b) Exclusive and shared subspaces normalized variance. In both panels, the stroke color represents the subspaces where neural activity was projected, and the fill color represents the activity being projected. In both panel Blu color refer to Move (M), red to Plan (P), magenta for shared (Sh). Example red column with blue stroke (PoM) represent the normalized variance of Plan activity projected in the Move subspace.

Acknowledgments

This research received funding from the European Research Council under the Grant Agreement No. 820213 (ThinkAhead), the Italian National Recovery and Resilience Plan (NRRP), M4C2, funded by the European Union – NextGenerationEU (Project PE0000006, “MNESYS”), the European Union’s Horizon H2020-EIC-FETPROACT-2019 Programme for Research and Innovation under Grant Agreement 951910

"MAIA".

References

Cui, H. (2014). From Intention to Action: Hierarchical Sensorimotor Transformation in the Posterior Parietal Cortex. *eneuro*, *1*(1), ENEURO.0017–14.2014. doi: 10.1523/ENEURO.0017-14.2014

Elsayed, G. F., Lara, A. H., Kaufman, M. T., Churchland, M. M., & Cunningham, J. P. (2016). Reorganization between preparatory and movement population responses in motor cortex. *Nature Communications*, *7*(1), 13239. doi: 10.1038/ncomms13239

Gamberini, M., Dal Bò, G., Breveglieri, R., Briganti, S., Passarelli, L., Fattori, P., & Galletti, C. (2017). Sensory properties of the caudal aspect of the macaque's superior parietal lobule. *Brain Structure and Function*. doi: 10.1007/s00429-017-1593-x

Gamberini, M., Passarelli, L., Fattori, P., & Galletti, C. (2020). Structural connectivity and functional properties of the macaque superior parietal lobule. *Brain Structure and Function*, *225*(4), 1349–1367. doi: 10.1007/s00429-019-01976-9

Jiang, X., Saggar, H., Ryu, S. I., Shenoy, K. V., & Kao, J. C. (2020). Structure in neural activity during observed and executed movements is shared at the neural population level, not in single neurons. *Cell Rep.*, *32*(6), 108006.

Kaufman, M. T., Churchland, M. M., Ryu, S. I., & Shenoy, K. V. (2014, March). Cortical activity in the null space: permitting preparation without movement. *Nature Neuroscience*, *17*(3), 440–448. doi: 10.1038/nn.3643

Medendorp, W. P., & Heed, T. (2019). State estimation in posterior parietal cortex: Distinct poles of environmental and bodily states. *Progress in Neurobiology*, *183*, 101691. doi: 10.1016/j.pneurobio.2019.101691