Neural Representations Interact Across Brain Regions Dynamically During Multi-step Action Sequences in Macaque Monkeys

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ABSTRACT:

Introduction: This study investigates the interaction between brain regions with distinct cognitive functions during action planning, execution, and termination, particularly in the context of macaque monkeys' drawing behavior. By examining inter-area neural connectivity, we aims to elucidate the dynamics of neural activities across different stages of action, despite the challenges posed by high-dimensional multi-neuron recordings.

Method: Decoders were trained to decode the shape representation from collected neural data. Cross-correlation and communication subspace methods were applied to decoding accuracy to quantify the interaction between each pair of brain regions across different time periods, with permutation tests to assess significance.

Result & Conclusion: We observed dynamic and significant inter-area correlations shifting from the PFC, premotor, to motor areas with time lags as action planning progressed to execution. Stronger connections followed with higher task complexities. The interactions between brain regions are dynamic during multi-step action sequences, with the premotor area acting as a hub. The results support specialized and gated inter-area interactions.

INTRODUCTION:

Dynamic interactions between brain regions with distinct cognitive functions, including spiking activities and their encoded neural representations, are widely assumed to be crucial for visual motor integration and compositionality during action planning, execution, and termination. However, since high dimensionality is a challenging problem when analyzing multi-neuron recordings, we still lack an understanding of flows of signals and their connectivity between brain regions for different neural representations, as well as how inter-region dynamics support multi-step action sequences with compositional symbolic systems. In this research project, we designed a symbolic model focusing on the drawing behavior of macaque monkeys. A significant part of the experiment was to test the inter-area interactions and communications across the brain, to uncover the dynamics of neural activities throughout different stages and types of action.

METHODS :

Decoding Neural Representation

Two macaques were trained to draw shapes displayed on a screen using learned action grammars. Their neural activities were recorded via 512 electrodes placed across multiple brain regions. Decoders in each brain region were trained from single-stroke trials, to compute moment-to-moment decoding scores during multi-stroke trials. The decoding accuracy for the shapes was extracted and normalized by subtracting the peri-stimulus time histogram (PSTH) across trials.

Inter-area Cross-correlation

Cross-correlation (xcorr) was computed for four stages to the dynamics of examine inter-area correlation and time lags: early action planning (0-900ms), late action planning (900-1800ms), the entire planning phase (0-1800ms), and the action execution phase (0-900ms). the coefficient was normalized by dividing the product of auto-correlations, and averaged across all trials. Permutation tests were used to assess the significance of cross-correlation coefficients, both by shuffling decoding accuracy across all trials and within each shape group of 10-neighboring trials. Significant cross-correlations with time lags within 200ms were reported.

Communication Subspace

To explore the dimensionality of inter-area correlation, firing rates were binned and smoothed by 100ms. Residuals were calculated by subtracting the PSTH. Reduced rank regression (RRR), factor regression (FR), and factor analysis (FA) were employed to determine the optimal predictive dimension, optimal dominant dimension, and dimensionality in the neural communication subspace between brain regions.
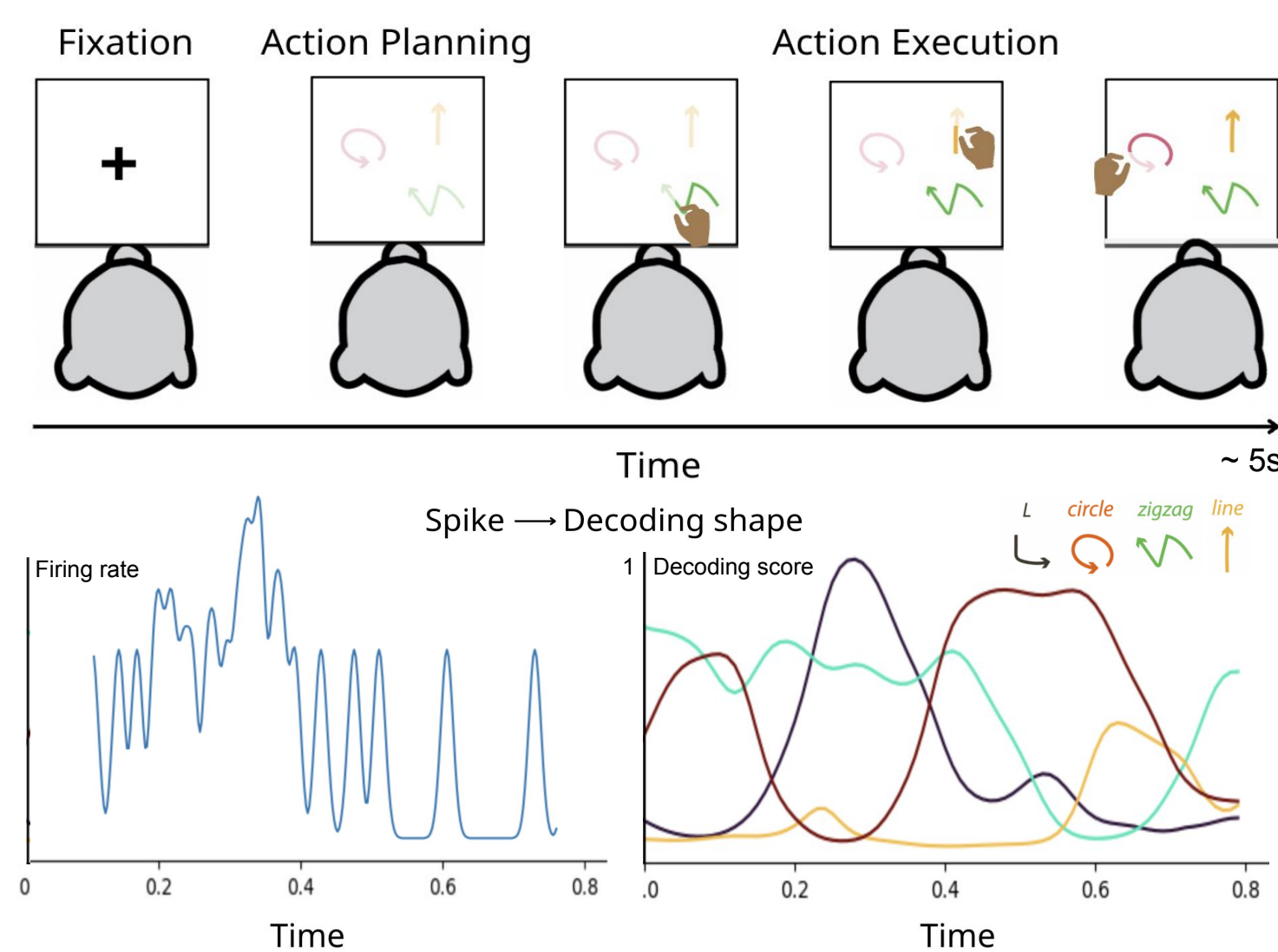

Figure 1. The schematic diagram of the experimental design, neural spikes recorded, and the decoding of neural representation. For each trial, macaque monkey was guided to draw single or multiple strokes of shapes in different locations of the board, and spike activities recorded across multi-neuron was used to decode the neural representation of shapes for different stages (timing) of each trial.
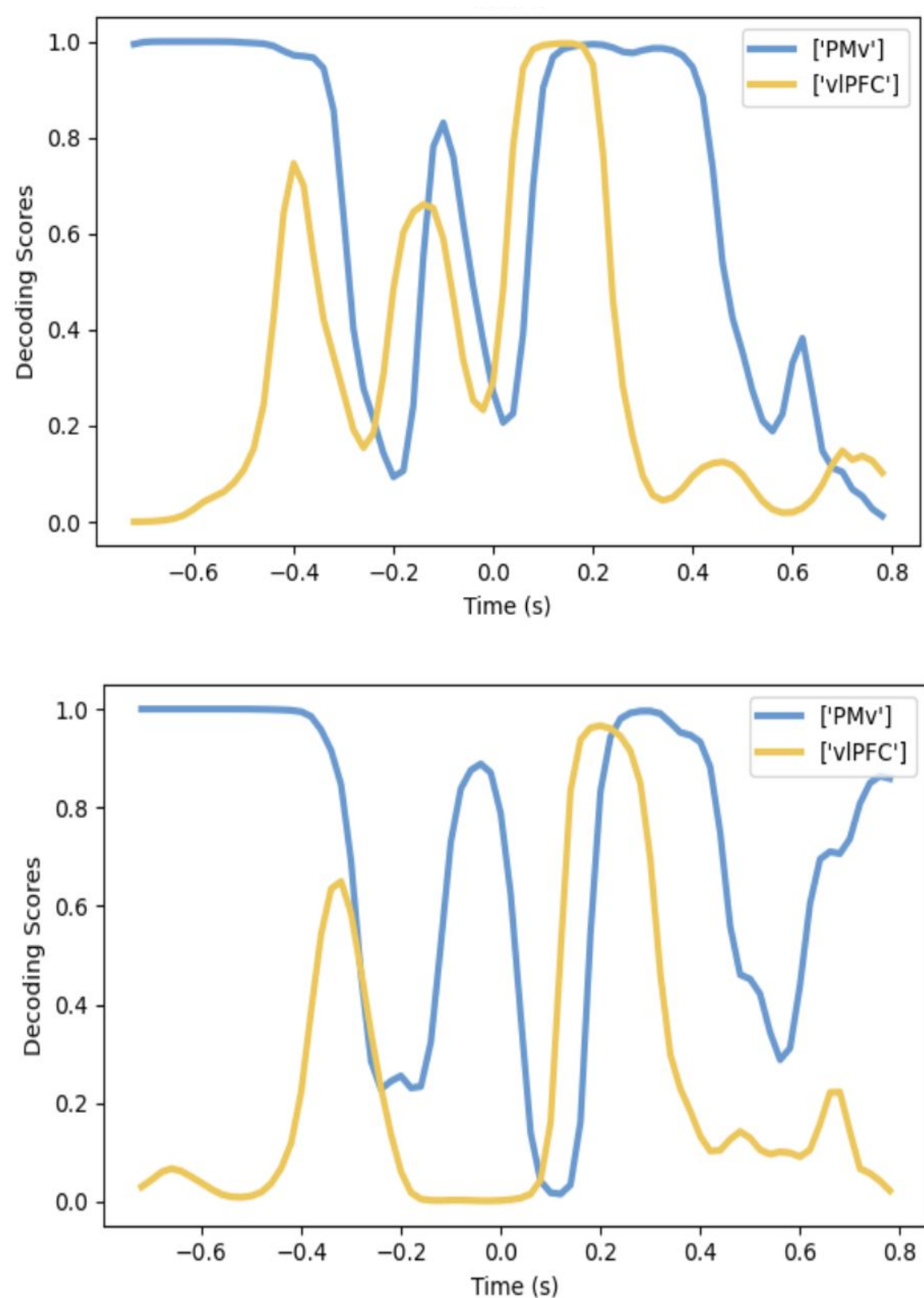

Figure 2. Two representative examples of inter-area interaction of decoding scores of shapes. Only the decoding score of the correct shape in each trial was extracted as decoding accuracy. These two figures indicates the leading of neural representation in the Ventrolateral prefrontal cortex (vlPFC) compared to premotor ventral area (PMv) with negative time lags, while the distribution of decoding accuracy strongly correlated with each region regardless of time lags between them.
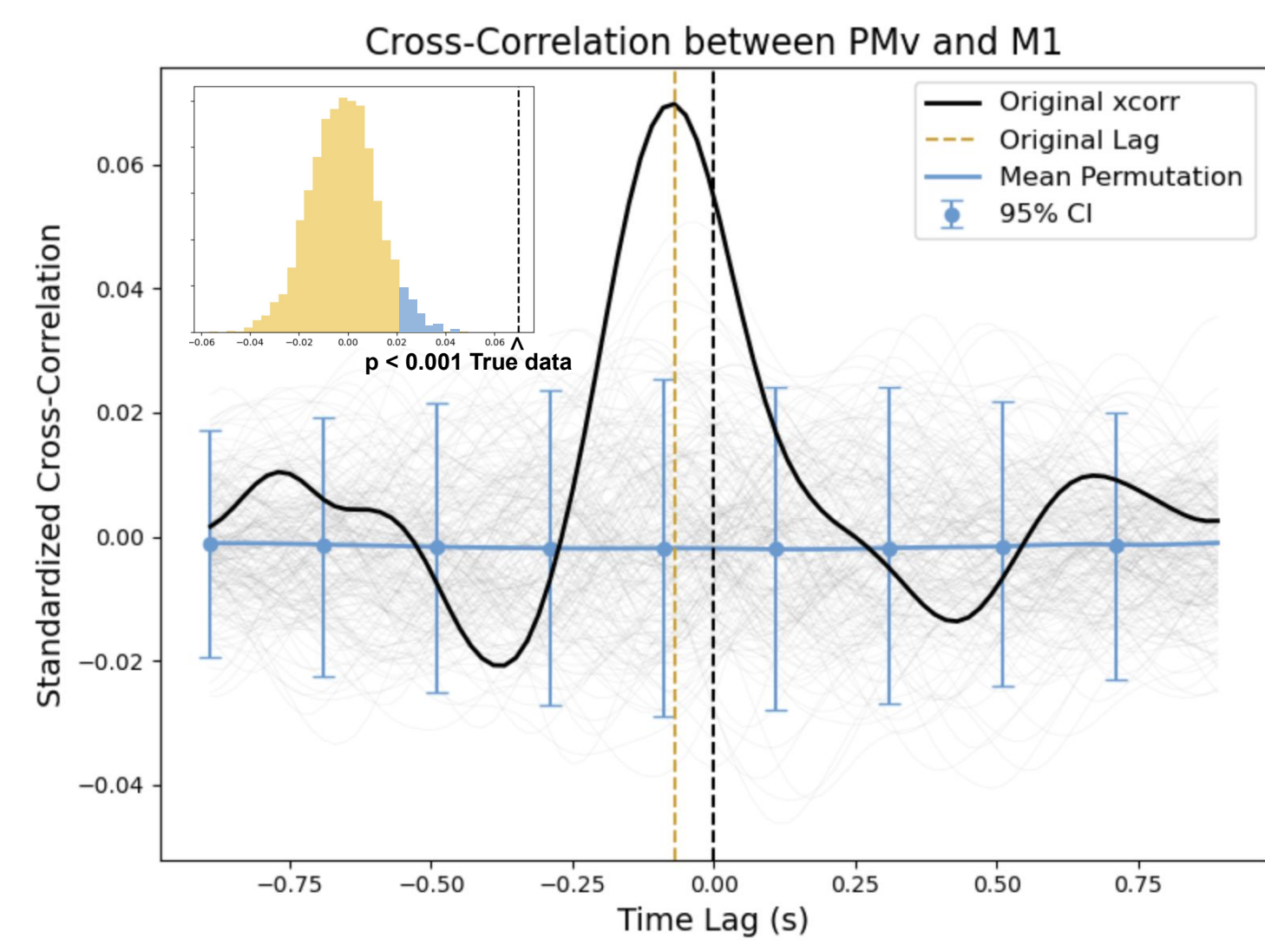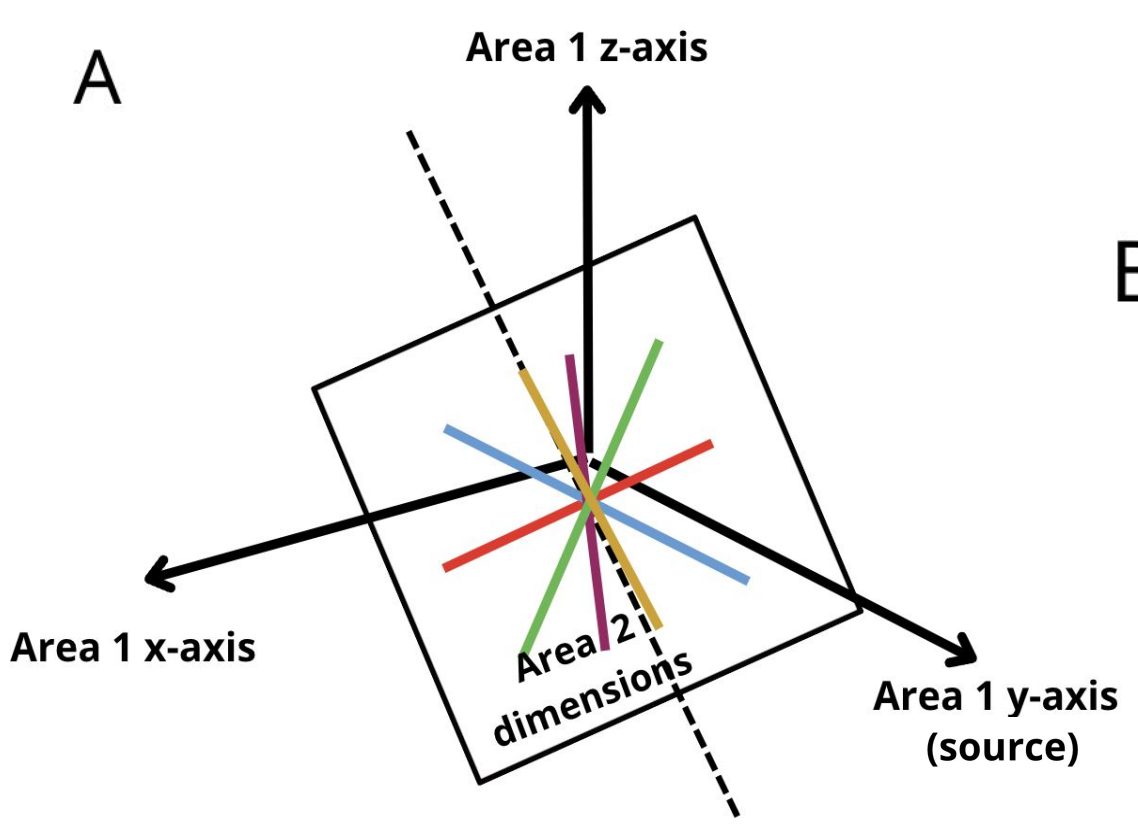

Figure 3. The cross-correlation between decoding accuracies of two brain regions. The horizontal blue line represents the averaged cross-correlation coefficient across time lags from 5,000 permutations with the 95% CIs, and the histogram displays the relative distribution of true cross-correlation compared to the permuted data.
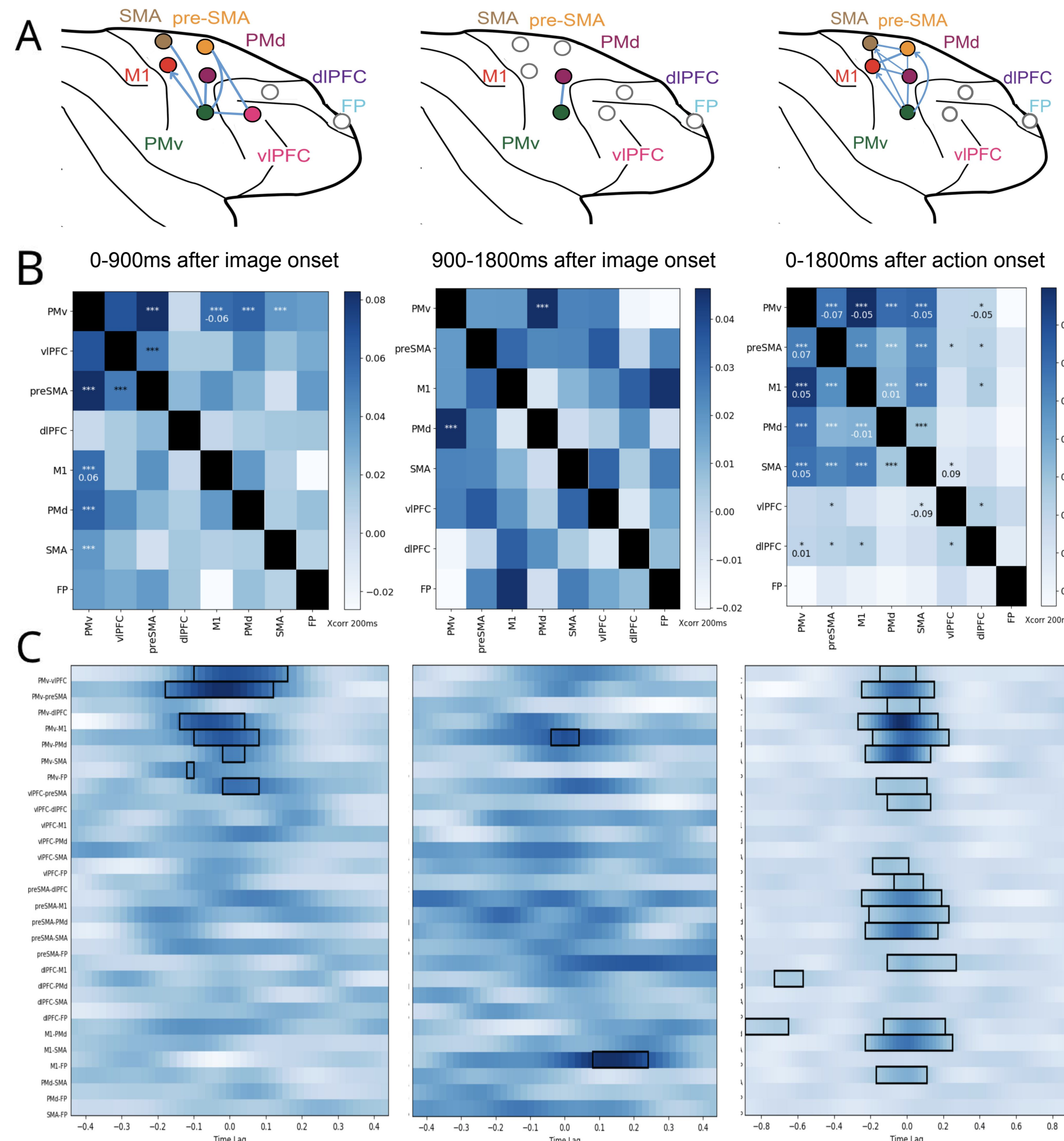

Figure 4. Summarized results of the strengths and time lags of cross-correlation (xcorr) between all pairs of brain regions recorded. **A)** Interactions between brain regions recorded. Blue lines indicate significant xcorr between connected two brain regions, while arrows indicate significant time lags, projected from the earlier to the later neural representation. **B)** Heatmap of averaged xcorr strengths within ± 200ms of the image/action onset. Stars* indicate significant xcorr while numbers represent significant time lags. **C)** xcorr across time lags. Squared regions have significant xcorr strengths after Bonferroni correction of multiple comparisons, while the scale of the same as (B.
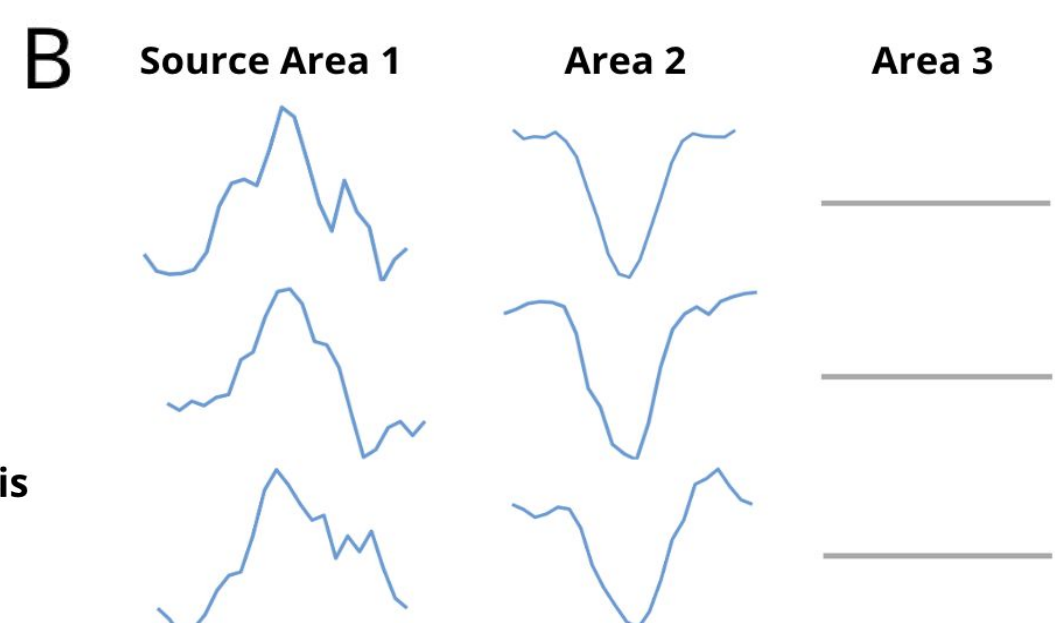

Figure 5. The schematic diagram of the hypothesis of "communication subspace". **A)** The source area 1 has a unique subset of "predictive dimensions" in a 2-dimensional subspace that can provide activities in the target area 2, compared to "private dimensions" without prediction roles. **B)** The activity of source neurons within the predictive dimensions can only be mapped to the neural activity in specific target area.
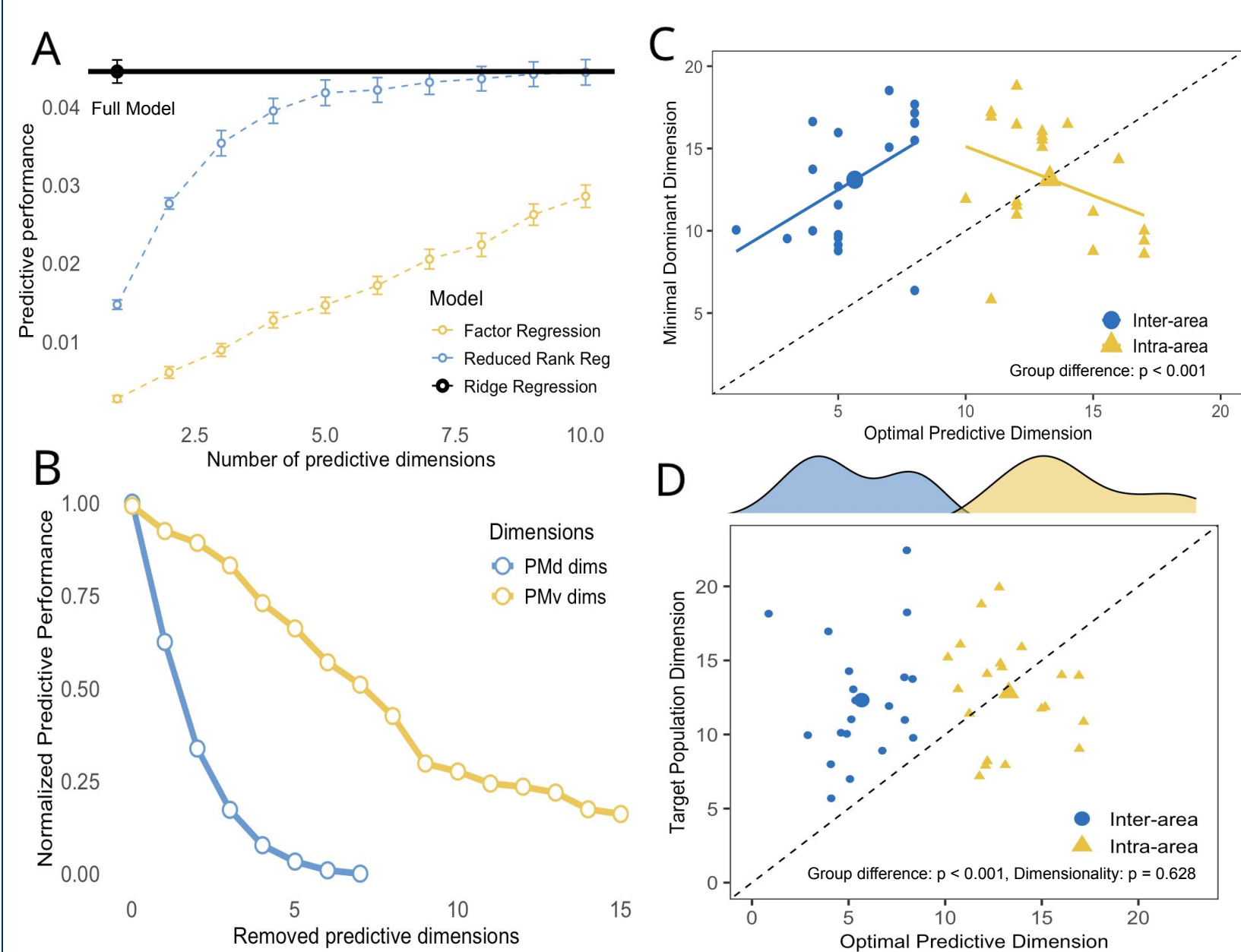

Figure 6. The results of regressions to test the dimensionalities of the communication subspace. **A)** The regression using PMv to predict the activities in PMd. Reduced rank regression and factor regression was used to include predictive and dominant dimensions, correspondingly. **B)** The change of predictive performance by sequentially removing the most predictive dimensions of inter-area and intra-area targets. **C, D)** The comparison of dimensionality, optimal predictive dimensions, and optimal dominant dimensions between inter-area and intra-area predictions.

RESULTS:

PMv demonstrated the highest decoding accuracy for shapes, with an average accuracy of 80%, while the frontal pole showed the least. The inter-area neural correlations varied dynamically across different stages of action planning and execution. Early planning stages involved stronger connections between the prefrontal cortex, premotor areas, and pre-supplementary motor areas, indicating a focus on abstract symbolic processing. As the process moved towards action execution, connectivity of brain regions shifted towards pre-motor, supplemental motor and motor areas, suggesting a transition from decision and planning to physical action.

Significant time lags were observed, with premotor areas including PMv and PMd leading most of motor and supplementary motor areas, indicating a potential hierarchical flow of action planning. As shape complexity, number of elements, and rules increased, the connection between brain areas tended to be stronger, suggesting that more complex compositionality requires inter-area communication and coordination. Despite similar levels of dimensionality within brain regions, inter-area communication utilized a small set of communication subspace, which appeared crucial for effective interaction between brain areas. Last but not least, the predictive performances were closely correlated with the strength of inter-area cross-correlation for each brain region pair.

CONCLUSIONS:

1. The interactions between brain regions are dynamic, with time lags related to stages of action planning and execution, task complexity, and brain region functions, indicating a hierarchical order in multi-step action sequences.

2. During the transition from early action planning to execution, significant correlations between brain regions gradually shift from the prefrontal cortex to motor and supplementary motor areas, while the premotor area, especially PMv, potentially serves as a hub of neural connectivity with a lead of neural representations.

3. While significant correlations exist across multiple brain regions, only a small subspace in specific areas has major or exclusive inter-area connections, implying the potential of dynamically gated transformations between subpopulations.

REFERENCES: