**Unbiased Estimation of Functional Dimensionality and Engagement in Naturalistic Movie Viewing**

Linshan Wang

Department of Psychology, McGill University  
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Dr. Reza Farivar-Mohseni

**Abstract**

Understanding how the human brain encodes depth-rich visual information remains a central question in neuroscience. While previous studies have identified regions responsive to stereoscopic input, they have largely overlooked the internal representational complexity within these areas. This study investigates how stereoscopic (3D) versus monoscopic (2D) naturalistic movie viewing modulates functional dimensionality and engagement across the visual cortex. Using a whole-brain searchlight-based principal component analysis (PCA) framework, we analyzed fMRI data from 55 participants viewing the same movie in both formats. Functional dimensionality was defined as the number of statistically significant principal components in each region, while engagement was measured as the total variance explained by these components. Our results demonstrate that 3D viewing increases both metrics across early, dorsal, and ventral visual areas, with the strongest enhancements in right-hemispheric dorsal regions such as MT and hMT+. Notably, ventral area hV4 showed comparable dimensionality increases, while LO exhibited the opposite. These findings suggest that stereoscopic input reorganizes neural encoding by enriching local population codes in a region- and hemisphere-specific manner, offering new insights into the cortical underpinnings of immersive visual perception.

**Introduction**

One important yet underexplored dimension of visual experience is the difference in neural processing between monoscopic (2D) and stereoscopic (3D) viewing. While 2D stimuli present a flat, depth-ambiguous image, stereoscopic vision engages additional cues—including binocular disparity, motion parallax, and perspective—to create the percept of immersive depth (Fleet et al., 1996; Chen et al., 2024; Korisky and Mudrik, 2021). In a 2D setup, both eyes are shown the same flat image, so objects at different depths appear identical to each eye, and no binocular disparity is present. In contrast, a 3D setup presents two slightly different images, mimicking how our eyes naturally view the world. These added perceptual demands likely engage the visual cortex not just more strongly, but differently, altering both the magnitude and the internal structure of neural representations.

Previous research in fMRI, neurophysiology, and behavioral neuroscience has identified brain areas involved in stereoscopic perception. Stereoscopic perception spans both early visual regions (Qian, 1997; Ohzawa et al., 1997) and higher-order areas across the dorsal and ventral visual streams. Notably, Other research has identified dorsal stream regions such as V3A, V7, and the intraparietal sulcus (IPS) as particularly sensitive to stereoscopic depth cues (Likova & Tyler, 2007; Preston et al., 2008; Minini et al., 2010). Likewise, the lateral occipital cortex (LO), which is part of the ventral stream has shown involvement in depth-based object processing.

3D viewing alters regional responses and enhances inter-subject synchrony in visual cortexx (Hassonet al., 2004; Gaebler et al., 2014), reflecting more temporally aligned processing across individuals during depth-rich stimuli. In a recent study by Zhang and Farivar (2020), inter-subject spatial pattern correlations were found to be stronger and more consistent during 3D compared to 2D movie viewing, particularly in visual cortex. These differences were non-uniform across brain regions, suggesting that functional components of 3D vision are both stimulus-driven and regionally specific. These findings support the idea that 3D vision reorganizes the way information is represented across different cortical areas on top of simply modulating activation level of each region.

However, most previous studies rely heavily on activation-based analyses, which assess how much a region activates but fail to capture *how* that region internally organizes or represents information. While useful, such methods may miss richer aspects of cortical processing (Kriegeskorte et al., 2006; Coutanche, 2013). Others have focused on functional connectivity (FC). While valuable, FC does not reveal the complexity of information encoded within each region (Anzellotti & Coutanche, 2018; Cohen & D’Esposito, 2016). Ng et al. (2021) showed that 3D input increases richness of local information encoding across visual cortex, which is an effect not captured by connectivity alone. Multivoxel Pattern Analysis (MVPA) has advanced the field by decoding spatial patterns of activity and showing that different conditions can elicit distinguishable neural responses (Norman et al., 2006). Yet MVPA is primarily a classification tool—it tells us whether patterns differ, but not how complex or high-dimensional those patterns are. Two regions may be equally classifiable but differ in how richly they encode stimuli (Diedrichsen & Kriegeskorte, 2017; Ahlheim & Love, 2018).

In contrast, some studies begun to emphasize local representational complexity, assessing how richly individual brain areas encode information. For example, Ahlheim & Love (2018) introduced a method for estimating the functional dimensionality of neural representations using singular value decomposition (SVD) combined with cross-validation and hierarchical Bayesian modeling. Similarly, Cunningham & Yu (2014) reviewed a family of dimensionality reduction techniques in neuroscience, emphasizing their value for uncovering latent structure in large-scale neural recordings and suggesting that local dimensionality reflects task-relevant computational capacity.

Therefore, we aim to move beyond the past works by examining the local functional complexity of fMRI signals. Rather than asking how much a region activates, or how it communicates with others, we ask how richly it encodes the structure of incoming stimuli.

The question we aim to address is: How does stereoscopic versus monoscopic naturalistic movie viewing modulate the functional dimensionality and engagement levels of specific visual cortical regions in the human brain? We focused on two key metrics: functional dimensionality, defined as the number of statistically significant principal components in a region’s time series, and engagement level, the total variance explained by these components.

To estimate these metrics, we developed a whole brain searchlight-based framework to estimate these properties across the cortical surface. Through this approach, we provide a detailed assessment of how 3D versus 2D viewing differentially engages specific visual areas and streams.

**Method**

The fMRI data used in this study were collected between 2018 and 2019 by Angela Zhang, involving 55 participants. During the scan, subjects watched a 5-minute clip from *Under the Sea 3-D: IMAX*, which subtended a visual angle of 17° × 9.4°. The clip was presented in both monoscopic (2D) and stereoscopic (3D) formats across two separate sessions, while participants maintained fixation on a central cross to minimize eye movement. Imaging was conducted using a full-body 3T Siemens TIM Trio scanner equipped with a 32-channel head coil for anatomical imaging and a 20-channel posterior coil for functional data acquisition.

We defined 36,001 searchlights across the cortical surface, each centered on a node and including its local neighborhood. The number of nodes per searchlight varied by cortical topology, but each node contributed a time series of 120 timepoints. For each searchlight, we applied principal component analysis (PCA) to the time series matrix (N nodes × 120 TR) to estimate the functional dimensionality. PCA decomposed the signal into orthogonal components, yielding eigenvalues that reflect the variance explained by each component.

**Figure.1 Schematic presentation of counting significant components**

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To assess significance, we used a Fourier phase scrambling procedure. This preserved the power spectrum of each time series while disrupting temporal structure. We repeated the scrambling and PCA 1,100 times to generate a null distribution of eigenvalues for each principal component. The 95th percentile (1,045th largest value) of the null distribution served as the significance threshold. We then compared the real PCA eigenvalues to the null thresholds and counted how many components exceeded significance—this count represented the dimensionality for each searchlight.

To relate these findings to visual system organization, we used a probabilistic visual atlas (Wang et al., 2015) to define 22 cortical visual areas, including early, dorsal, ventral, and higher-order regions. These ROIs were used to group searchlights and compare dimensionality and engagement across sub-regions of the visual hierarchy.

**Result**

The cortical maps of statistically significant principal components under 2D and 3D viewing conditions shows a similar spatial distribution across the viewing condition. Visually, in both cases there is a noticeable gradient of increasing componemts from early visual areas toward higher-level regions (Figure 2).

**Figure 2. Cortical map of number of significant components across conditions**

*Number of significant principal components mapped on the SUMA cortical surface for (a) 2D movie viewing and (b) 3D movie viewing. A close-up of a brain

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The absolute difference in the number of significant components between 3D and 2D viewing is positive across most visual areas. This trend is evident in both hemispheres, with variation across regions (*Figure 3a*). When grouped by visual processing stream, dorsal regions show the highest average difference in component ¸\*count, followed by early and ventral areas (*Figure 3b*). We conduct further analysis to compare right with left dorsal stream. Right hemisphere dorsal regions show a significantly greater increase compared to the left (*Figure 3c*).

**Figure 3 Measure of Component Difference per searchlight (3D-2D)**

*(a) Mean absolute difference in significant principal components (3D − 2D) for each visual area, separated by left (LH) and right (RH) hemispheres. Error bars represent standard error of the mean.*

*(b) Aggregated comparison across early visual, ventral, and dorsal streams.*

*(c) Focused comparison of dorsal stream differences between hemispheres, showing significantly greater differences in the right hemisphere (p < 0.05).* A graph with red and white lines

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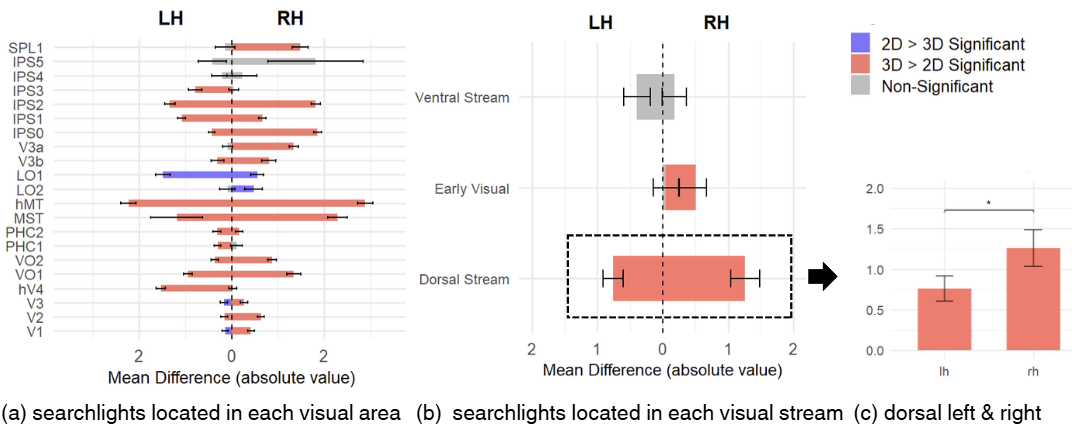
The total variance explained by the significant components is also generally higher in 3D than 2D viewing. This pattern is consistent across regions in both hemispheres (*Figure 4a*). When aggregated across streams, dorsal areas again exhibit the largest difference, with early and ventral streams showing smaller increases (*Figure 4b*). The right hemisphere dorsal stream shows a significantly greater increase in explained variance than the left (*Figure 4c*).

**Figure 4 Measure of Engagement Difference per searchlight (3D-2D)**

(a) Mean absolute difference total variance explained by significant principal components (3D − 2D) for each visual area, separated by left (LH) and right (RH) hemispheres. Error bars represent standard error of the mean.

(b) Aggregated differences across early visual, ventral, and dorsal streams.

(c) Focused comparison of dorsal stream differences between hemispheres, showing significantly greater 3D-2D differences in the right hemisphere (p < 0.05).

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**Table1. Region-wise comparison of functional components per searchlight between 3D and 2D movie**

*Mean number of significant principal components for searchlights center located in each ROI during 3D and 2D movie viewing conditions, reported separately for the left (top) and right (bottom) hemispheres.*

*Results show the mean ± 95% confidence interval, along with the t-statistics and significance levels from paired-sample t-tests.*

*\*\*\* indicates p < 0.05; ns = not significant.*

*The number of nodes/searchlights within each ROI is also reported.*



**Discussion**

Prior research on stereoscopic visual processing has largely focused on identifying the brain regions activated by depth cues using univariate analyses or functional connectivity measures. These approaches have consistently implicated both early visual areas (e.g., V1–V3) and higher-level dorsal stream regions such as V3A, V7, and the intraparietal sulcus (Likova & Tyler, 2007; Preston et al., 2008; Minini et al., 2010), as well as ventral areas like the lateral occipital cortex (LO) involved in object-level depth perception. More recent studies revealed that 3D stimuli can enhance cross-brain alignment and coordination (Hasson et al., 2004; Zhang & Farivar, 2020). However, these methods are limited in their ability to characterize the internal representational richness within individual regions. In this study, we addressed this gap by applying a whole-brain searchlight PCA approach to estimate the functional dimensionality and engagement levels of cortical responses. We employed a visually rich, naturalistic stimulus presented under both 2D and 3D viewing conditions and collected fMRI data from a large sample of participants (N = 55), and analyses were conducted using stringent statistical methods with minimal underlying assumptions (Nichols & Hayasaka, 2003). To reduce the influence of top-down cognitive factors, the stimulus was designed to be perceptually engaging but lacked narrative content, and participants maintained central fixation to ensure experimental consistency (Naci et al., 2014; Lu et al., 2016).

**3D movie viewing elicits richer representational structure.**

A core finding from our study is that the functional complexity is not static—it varies systematically by viewing condition. 3D movie viewing elicited a greater number of significant components and higher total variance explained compared to 2D, indicating enhanced representational complexity and stronger engagement.

The enhancement in functional complexity and engagement is not confined to a single pathway. Most visual regions—across early, ventral, and dorsal regions, show more functional components under 3D viewing than 2D. This broader engagement implies that stereoscopic information percolates across the entire visual hierarchy, affecting how scenes are processed at multiple levels. From early visual areas to higher-order regions, evidence showed that the representational structure across visual cortex becomes richer when 3D spatial cues are available.

**Dorsal - ventral dissociation and association in stereoscopic**

Traditionally, the processing of depth in the human visual system has been associated predominantly with the dorsal visual stream. This pathway—often characterized as the "where/how" stream—is known for its role in spatial localization, motion tracking, and visually guided action. Consistent with this view, numerous studies have highlighted dorsal regions such as MT, hMT+, V3A, and IPS as central hubs for integrating binocular disparity, motion-in-depth, and other stereoscopic cues (Likova & Tyler, 2007; Preston et al., 2008; Minini et al., 2010).

Our findings reinforce this classical perspective, revealing a pronounced increase in functional dimensionality and engagement levels across dorsal areas during 3D movie viewing. In particular, MT and hMT+ showed among the strongest enhancements in both the number of significant components and the variance they explained—suggesting that these regions not only become more active but also encode richer and more diverse patterns of visual information when spatial structure is more complex.

However, the long-standing dorsal-ventral dissociation in depth perception is increasingly being challenged. These finding challenges overly rigid dichotomies between the two streams—the dorsal stream is traditionally associated with spatial processing ("where/how") and the ventral stream with object recognition ("what"). Historically, depth perception was thought to be dominated by the dorsal stream. Recent studies suggest that the ventral stream, traditionally seen as the "what" pathway involved in object recognition, also contributes to depth-based processing. Evidence points to ventral regions participating in 3D object structure encoding, surface curvature, and volumetric scene interpretation, particularly under naturalistic or dynamic conditions (Farivar, 2009; Henson, 2016; Georgieva et al., 2009).

Our findings provide a new layer of support for this perspective. While dorsal areas exhibited the most enhancement, we observed a unidirectional trend across nearly all visual regions, including those in the ventral stream. Although the aggregate difference in the ventral stream reached statistical significance only in the left hemisphere, individual ventral areas still demonstrated significant increases in representational complexity under 3D viewing. This general enhancement pattern challenges the idea that depth processing is confined to the dorsal pathway only.

In particular, hV4 stood out within the ventral stream. As a mid-level visual area involved in color, shape, and curvature processing, hV4 showed striking increase in functional components under 3D conditions—comparable in magnitude to that observed in MT in dorsal stream. Previous electrophysiological evidence found that MT neurons responses reflect a fast, correlation-based mechanism. In contrast, V4 neurons showed more selective and correspondence-sensitive tuning, especially reduced responses to anticorrelated stimuli, which indicates more complex, match-based disparity processing. Their findings suggest that MT and V4 support complementary roles in depth perception. MT extracts fast disparity signals, while V4 encodes refined spatial structure (Thomas and Henson, 2011). In our study, both areas showed similarly strong increases in functional components during 3D viewing. which reinforces the idea that, V4 maybe as important as MT for stereoscopic vision, and each is tuned to different aspects of binocular information. Their shared enhancement likely reflects distinct but equally critical contributions to building rich 3D percepts.

Interestingly, not all visual areas followed the unidirectional trend. LO (lateral occipital cortex) which is another ventral region was the notable exception to this general trend. Unlike all other areas, LO exhibited a significant decrease or negligible change in functional components and engagement during 3D viewing. Consistent with previous study, Snow et al. (2011) found that LO showed stronger repetition suppression for 2D pictures than for real 3D objects, suggesting that it may be less engaged—or differently tuned—when full stereoscopic cues are present. In our study, the availability of rich depth information in 3D stimuli may have shifted the burden of processing from LO to other ventral areas like hV4, which are more sensitive to 3D surface structure. This divergence suggests that not all ventral stream regions contribute equally to stereoscopic perception, and that LO’s role may diminish when 3D cues dominate the visual scene.

**Hemispheric Asymmetry in dorsal stream**

While both hemispheres exhibited increased functional complexity and engagement during stereoscopic viewing, a notable hemispheric asymmetry emerged: the right dorsal visual stream showed significantly greater enhancement in 3D–2D difference scores compared to the left. This asymmetry aligns with prior evidence suggesting a right-hemispheric dominance for spatial attention and depth processing. Studies using fMRI and lesion analyses have reported that the right parietal cortex is more engaged during tasks involving egocentric spatial judgments and depth-based navigation (Fink et al., 2001; Gitelman et al., 1999; Thiebaut de Schotten et al., 2011). Similarly, Parker and Duffy (2007) found that right-lateralized dorsal areas were more responsive to motion-in-depth cues, while Corballis (2003) argued for a broader right-hemisphere specialization in visuospatial integration. Our results build on this literature by showing it encodes a more diverse representation of depth, as indicated by greater increases in both the number of functional components and the variance they explain. This suggests that the right dorsal stream may be particularly tuned to the computational demands imposed by depth-rich, naturalistic stimuli.

Together, these results support a view of the visual cortex as a flexibly organized system, in which functional components dynamically adapt to environmental demands. Under stereoscopic viewing, both dorsal and ventral visual streams exhibit increased representational complexity, reflecting a global recalibration of visual processing in response to richer spatial input. The magnitude and pattern of this recalibration are not uniform across the cortex. Dorsal regions, particularly in the right hemisphere, exhibited more pronounced enhancements in functional dimensionality and engagement than their ventral or left-hemispheric counterparts. These findings suggests that the brain reallocates computational resources in a targeted, functionally relevant way when processing complex 3D visual environments.

**Technical advancement and limitations**

This study combined dimensionality extraction method with searchlight analysis, a powerful technique for examining fine-scale neural representations (Braver et al, 2013). Rather than averaging over large brain regions, the searchlight method scans small circular clusters across the brain, making it highly sensitive to local changes in information content. This is especially important when investigating the subtle but distributed differences in neural processing (Zhang and Farivar, 2020; Tahmasebi et al, 2012). To ensure that results were statistically valid, we employed Fourier phase randomization in a permutation-based statistical framework. This approach preserves the temporal structure of fMRI signals while creating a robust null distribution (Handwerker et al, 2012; Schreibe and Schimitz, 2000), thereby controlling false positives.

While PCA offers a powerful way to reduce dimensionality and capture dominant patterns in fMRI data, it comes with notable limitations. One key disadvantage is the loss of biological interpretability—the resulting components are mathematical abstractions that may not correspond to anatomically or functionally distinct brain systems(Calhoun et al 2009). PCA relies on the assumption of linearity, meaning it only captures linear relationships between voxels and may non-linear interactions that are common in neuron responses (Darbin et al 2025; He and Yang, 2020; Briggs et al 2004; Shinn 2023). We argue that this model is reasonable for the current study. First, the goal of our analysis was not to model the full complexity neural responses, but rather to measure how much independent variation exists within spatially confined regions. PCA remains one of the most effective tools for this purpose. Second, although neural activity includes non-linear dynamics, many studies have shown that linear approximations can capture a substantial proportion of meaningful variance in data in early sensory and associative cortices (Haxby et al., 2001; Norman et al., 2006).

Another limitation in our principal components count arises from the overlap between searchlights, which can lead to redundant sampling of voxel activity across neighboring regions. Because each searchlight includes partially overlapping sets of voxels, the same neural signals may contribute multiple times to different local PCA calculations. Additionally, overlap complicates spatial interpretation, as it's unclear whether high component counts reflect true local complexity or are influenced by neighboring activity patterns. However, given that the size of our searchlight is medium (5mm radius), the impact of overlapping on principal component counts is somewhat mitigated. Medium-sized searchlights are large enough to capture meaningful local patterns, but not so extensive that overlap dominates the analysis. This means that while some redundant sampling still occurs due to shared voxels between neighboring searchlights, the effect on dimensionality inflation is likely moderate rather than severe.

**Statement of Contribution**

The fMRI data used in this study were originally collected and preprocessed by Angela Zhang as part of her doctoral research. Angela Zhang was responsible for designing and conducting the original experiment, including stimulus presentation and acquisition protocols. The current study builds on this dataset to investigate new research questions focused on local complexity during 2D and 3D naturalistic viewing. All analyses, including the implementation of the searchlight-based PCA framework, statistical modeling, and interpretation of results, were carried out by Linshan Wang.

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