

Detection of object motion during self-motion: psychophysics and neuronal substrate

Finnegan J. Calabro¹, Lucia M. Vaina^{1,2}

¹Brain and Vision Research Laboratory, Department of Biomedical Engineering, Boston University, Boston, MA, USA

²Harvard Medical School, Department of Neurology, Boston, MA, USA

fcalabro@bu.edu, vaina@bu.edu

Introduction

During self-motion, the separation of the motion flow field into self- and object-motion components is critical to safe navigation.

"Flow-parsing", a visual-only implementation, has been proposed based on the subtraction of induced self-motion from the perceived flow field^{1,2}.

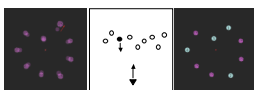


Is object detection during forward observer translation consistent with the flow-parsing hypothesis?

What brain networks mediate the detection of object motion by a moving observer?

Psychophysics

Task

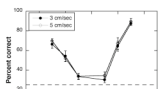


Subjects (n=23, ages 18-30) viewed 9 textured spheres (1.5° mean diameter). Objects were moved and scaled during 1 sec of simulated forward observer motion, with one object (the "target") given an additional, independent motion component towards or away from the observer. Subjects had to identify the target after the end of the stimulus.

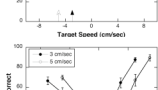
Could strategies other than flow parsing explain performance?

Results

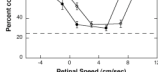
Could observers have selected the target based on retinal motion?



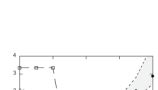
Varied the speed of observer motion (3, 5 cm/sec), which shifted the retinal speed of all objects.



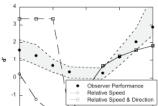
Performance dependent on the target object speed, not the retinal speed³.



Alternatively, could subjects be using relative motion among the objects?



Computed expected performance if subjects picked a target defined by speed and/direction relative to the other objects.



Neither prediction could account for subject performance.

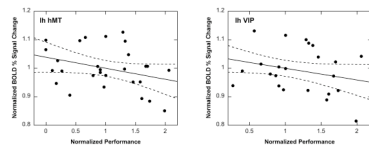
Functional Activation

Seven of the subjects involved in the psychophysical experiment also participated in an event-related fMRI study using the object motion detection during self-motion task.

Regions of interest (ROIs) were selected based on clusters of at least 8 significantly active ($p < 0.01$) voxels, and which were present in at least 5 of 7 subjects, based on a contrast between the motion and an off period containing static objects. ROIs were named based on functional descriptions in the literature where available, and anatomical structure otherwise.

There were 7 bilateral and 3 LH ROIs, distributed among the occipital, occipito-temporal, parietal and parieto-frontal regions.

No ROIs showed statistically significant correlations to behavior, though lh hMT and lh VIP were suggestive of an inverse relationship ($p = 0.089$ and 0.080 respectively). These ROIs therefore seem to be most directly linked to behavior.

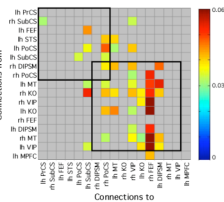


Brain Networks

To determine how ROIs interact in this psychophysical task, we computed connectivity among functionally defined areas using multivariate Granger causality.

A node reordering algorithm⁴ was used to determine community structure among all ROIs. We found two coarsely separated networks:

- A network of visually responsive areas: bilateral KO (V3D), hMT, VIP and left DIPSM.
- A network of higher-level, primarily left-hemispheric areas, including PoCS, MPFC STS and FEF, as well as bilateral SubCS and right DIPSM



Imaging Methods

MRI

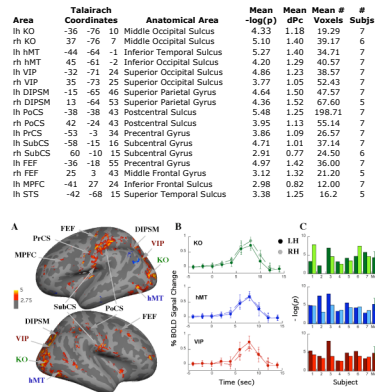
- 3T Siemens TrioTim 60 cm (RF coil ID) whole-body MRI.
- Two high resolution, 3D T1-weighted structural MRI scans obtained for registering the functional data using a 3D magnetization-prepared rapid acquisition gradient echo (MPRAGE) sequence (TR 2530 ms, TE 3.39 ms, inversion time 1100 ms, flip angle 7°)
- 128 slices of 1.33 mm thickness, and 256x256 in plane sampling (1x1 mm resolution).

fMRI

- Interleaved, gradient echo EPI sequence
- TR 2000 ms, 180 TRS; TE 30 ms, flip angle 90°, distortion factor=20%, phase=100
- Four 6-min acquisitions per subject. Event related stimulus presentation, with 40 trials per acquisition.
- 33 slices of 3 mm thickness were collected spanning the entire cerebral cortex, with in-plane sampling of 64x64 (resolution of 3.125x3.125 mm)
- Motion corrected (AFNI) and preprocessed with a 5mm FWHM spatial smoothing kernel (FreeSurfer)
- Group activation computed using weighted random effects GLM.

Connectivity

- Multivariate Granger causality⁵ among functionally defined ROIs
- Used slice-time corrected time-courses averaged across functionally active voxels
- First order AR model, based on Bayesian Information criterion
- p-values computed based on F-distribution
- Individual significances combined using Fisher's method. Group significance corrected for multiple comparisons using FDR < 0.001.

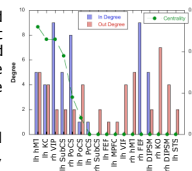


(A) Weighted random effects model of group activation (n=7) on the object motion task compared to an interval with static objects registered to the MNI155 standardized brain. Color indicates significance of activation (-log(p)). (B) Time courses for selected ROIs (VIP, KO and hMT). Error bars indicate ±1 standard deviation across subjects. (C) Mean significance (-log(p)) for each subject for the same ROIs. Dark dots/bars show LH data, light dots/bars are RH.

Network hubs

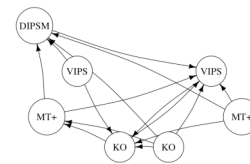
To evaluate the importance of the functionally active ROIs involved in the networks, we computed degree (number of connections) into and out of each ROI, and betweenness centrality (the proportion of shortest paths along which each ROI falls).

- lh hMT, lh KO and rh VIP had the highest centrality.
- lh hMT and lh KO had similarly high in and out degree, while rh VIP had significantly higher in degree than out degree (more incoming connections).
- rh FEF and rh PoCS had many incoming connections, but low centrality



Conclusions

- Our fMRI data suggest that the neural substrate for the stimulus representation consists of a network of highly active and interconnected visual motion areas: KO, hMT, VIP and DIPSM.



- KO, hMT and VIP were the major hubs in the network, with both high degree and centrality.
- The high *in-degree* of VIP suggests it plays a critical role in the representation of the stimulus⁶.
- The high *in- and out-degree* of hMT and KO suggest they are critical in processing the visual information.
- Psychophysical performance on the task of object motion detection during simulated forward self-motion is consistent with the use of "flow-parsing". The significant involvement of KO may provide the neural substrate for the motion subtraction stage⁷ of "flow-parsing".

References

- Warren, P.A. and S.K. Rushton, Evidence for flow-parsing in radial flow displays. Vision Res, 2008. 48(5): p. 655-63.
- Rushton, S.K. and P.A. Warren, Moving observers, relative retinal motion and the detection of object movement. Curr Biol, 2005. 15(14): p. R542-3.
- Calabro, F.J., S. Soto-Faraco, and L.M. Vaina, Acoustic facilitation of object movement detection during self-motion. Proc Biol Sci, 2011.
- Rubinov, M. and O. Sporns, Complex network measures of brain connectivity: uses and interpretations. Neuroimage, 2010. 52(3): p. 1059-69.
- Seth, A.K., A MATLAB toolbox for Granger causal connectivity analysis. J Neurosci Methods, 2010. 186(2): p. 262-73.
- Duhamel, J.R., C.L. Colby, and M.E. Goldberg, Ventral intraparietal area of the macaque: congruent visual and somatic responses. J Neurophysiol, 1998. 79(1): p. 126-36.
- Tyler, C.W., et al., The specificity of cortical region KO to depth structure. Neuroimage, 2006. 30(1): p. 228-38.

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