Dynamical changes in functional organization resolve ambiguous motion perception

Alessandra Pizzuti (a.pizzuti@maastrichtuniversity.nl)
Department of Cognitive Neuroscience
Faculty of Psychology and Neuroscience,
Maastricht University, Maastricht, NL

Irene Acero Pousa (irene.acero@alumni.esci.upf.edu)
Department of Information and Communication Technologies, Center for Brain and Cognition,
Universitat Pompeu Fabra, Barcelona, ES

Omer Faruk Gulban (faruk.gulban@maastrichtuniversity.nl)
Brain Innovation B.V., Maastricht, NL,
Department of Cognitive Neuroscience,
Faculty of Psychology and Neuroscience,
Maastricht University, Maastricht, NL

Judith Carolien Peters (j.peters@maastrichtuniversity.nl)
Department of Cognitive Neuroscience
Faculty of Psychology and Neuroscience,
Maastricht University, Maastricht, NL

Gustavo Deco (gustavo.deco@upf.edu)
Department of Information and Communication Technologies, Center for Brain and Cognition,
Universitat Pompeu Fabra, Barcelona, ES
ICREA, Institut Català de Recerca i Estudis Avançats, Barcelona, ES

Rainer Goebel (r.goebel@maastrichtuniversity.nl)
Brain Innovation B.V., Maastricht, NL,
Department of Cognitive Neuroscience,
Faculty of Psychology and Neuroscience,
Maastricht University, Maastricht, NL

Abstract

Visual perception typically aligns with sensory input, but under bistable conditions, identical stimuli can lead to alternating percepts. While prior work has emphasized perceptual switches, less is known about how the brain stabilizes perception post-switch. Using 7T fMRI, we studied nine participants viewing a bistable motion quartet that induced spontaneous alternations between vertical and horizontal motion. Perceptual transitions involved dynamic interactions between hMT+ and frontoparietal regions (area 46, PF, PFm), while sustained perception engaged hMT+ and the intraparietal areas. Computational modeling revealed increased hierarchical complexity during ambiguity resolution, with frontal and parietal regions ascending in the functional hierarchy. These findings offer important constraints for modeling how the brain organizes itself to resolve perceptual ambiguity, and more broadly, how it supports conscious experience.

Keywords: Ambiguous Motion Perception; 7T fMRI; Whole-brain Network Connectivity; hMT+; DLPFC; bistable stimuli

Introduction

Conscious perception reflects brain processes that infer meaning from ambiguous input, supported by hierarchical brain networks that adapt to computational demands. Quantitative measures of hierarchical organization (network asymmetry and trophic coherence) distinguish brain state complexity (Deco, 2022; Kringelbach, 2024). Bistable stimuli offer a unique tool to study conscious perception, eliciting spontaneous perceptual switches under constant sensory input. For bistable motion tasks, while the crucial role of hMT+ is established (Schneider, 2019), it remains unclear how its connectivity patterns with the fronto-parietal network (Brascamp, 2018) reconfigure from perceptual transitions to support sustained perception. Using the ambiguous motion quartet stimulus (Schneider, 2019), we dissociated neural responses during transitions and sustained states with 7T fMRI. As controls, we included a physical (unambiguous) motion quartet and resting-state scans. We found distinct connectivity patterns characterizing perceptual switches and sustained perception, together with an increased hierarchical organization during ambiguity resolution, highlighting dynamic reconfiguration in support of conscious perception.

Results

Dissociating Transient and Sustained Neural Signatures During the Ambiguous Motion

During ambiguous motion, participants alternated between perceiving horizontal and vertical motion despite constant visual input. We hypothesized that perceptual transitions and sustained perception rely on distinct neural dynamics, which we tested using two general linear models: a "switch" model for perceptual transitions and a "block" model for sustained states. Both models explained neural activity during ambiguous motion (Figure 1A), whereas only the block model fit the physical motion condition (control). Using the Glasser parcellation (Glasser, 2016), we found that perceptual transitions (switch model) engaged hMT+ and higher-order regions, including dorsal visual areas, frontal area 46, and the PF and PFm complex. In contrast, sustained perception (block model) also involved hMT+, along with intraparietal areas, the frontal eye fields (FEF), and area 6. Within the motion complex hMT+ (Sulpizio, 2019), V4t showed predominantly switch-related activity, whereas MT, MST, and FST were primarily associated with block-related activity (Figure 1B). Our results support previous findings showing a crucial role for hMT+ in resolving motion ambiguity (Schneider, 2019), as well as the involvement of the fronto-parietal network during bistable tasks (Leopold, 1999; Knapen, 2011; Brascamp, 2018). Importantly, our findings uniquely reveal a functional dissociation between distinct neural mechanisms underlying transient versus stable percepts during ambiguous motion.

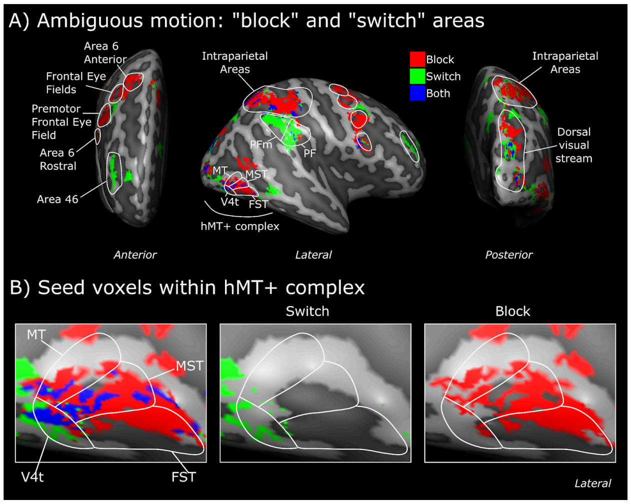

Figure 1. *Group model-map for the ambiguous motion condition (MNI space, Glasser parcellation). A) Probabilistic maps thresholded at nr of participants > 4 were binarized and compared voxel-wise to create a categorical map: red = block model, green = switch model, blue = both. B) Zoom-in on hMT+ shows model-specific responses.*

Lag-Based Functional Connectivity During Ambiguous Motion Perception

During perceptual transitions, hMT+ exhibited drive over frontal area 46 and PFm, with incoming connectivity from PF (p<0.001, corrected) (Figure 2A). In contrast, the physical motion condition (control) showed no outgoing modulation from hMT+. During sustained perception, a non-significant modulation between hMT+ and intraparietal areas suggested a possible bidirectional exchange (Figure 2B). Similar input to hMT+ from area 6 and FEF across tasks points to a shared attentional mechanism stabilizing motion perception. Finally, the observed directional connectivity from hMT+ to area 46 during perceptual transitions supports the role of dorsolateral prefrontal cortex in post-decision attentional processes (Brascamp, 2018).

Enhanced Asymmetry and Reduced Feedback Loops During Ambiguous Motion Perception

We used a generative effective connectivity (GEC) model (Kringelbach, 2024) to compare brain network organization across ambiguous motion, physical motion, and rest.

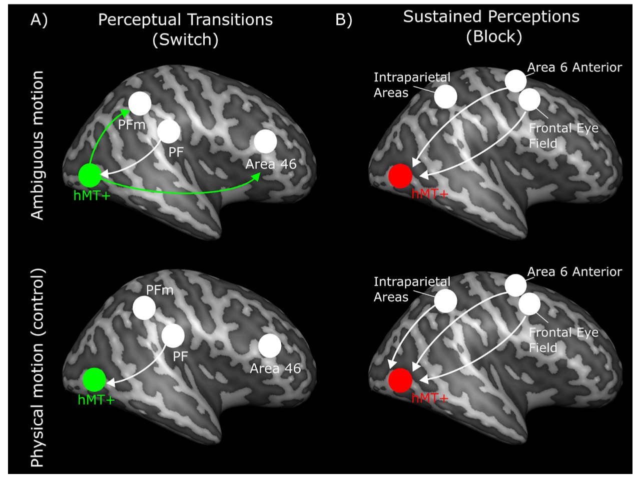

Figure 2. *Lag-based functional connectivity analysis (MNI space, Glasser parcellation). Arrows represent significant directional connectivity between hMT+ seed and target areas (p<0.001, corrected) during the perceptual transitions (A) and (B) sustained perceptions evaluated for both the ambiguous and the physical (control) motion condition.*

The ambiguous condition showed the highest connectivity asymmetry and lowest trophic coherence (p<0.001, corrected), suggesting a more hierarchical, stable network with fewer feedback loops, as expected due to its higher cognitive demand. Most regions decreased in centrality from physical to ambiguous conditions, except for a subset, including frontal area 46, area PF, and intraparietal areas, that increased. These results highlight a dynamic reorganization of network structure to support perceptual disambiguation.

Conclusions

Our findings reveal how the brain dynamically reorganizes to resolve perceptual ambiguity, with distinct frontoparietal interactions with hMT+ during transitions and sustained perception. This flexible hierarchy highlights the brain's adaptability and sets the stage for probing the networks' causal roles in conscious perception.

Acknowledgments

This project was funded by the EU-project H2020-860563 euSNN and the European Union's Horizon 2020 Framework Program for Research and Innovation under the Specific Grant Agreement No. 945539 (Human Brain Project SGA3). In-vivo fMRI data was acquired at Scannexus (Maastricht, the Netherlands). OFG is funded by Brain Innovation.

References

Glasser, M., Coalson, T., Robinson, E. et al. A multi-modal parcellation of human cerebral cortex. Nature 536, 171–178 (2016). https://doi.org/10.1038/nature18933

Brascamp J, Sterzer P, Blake R, Knapen T. Multistable Perception and the Role of the Frontoparietal Cortex in Perceptual Inference. Annu Rev Psychol. 2018 Jan 4;69:77-103. doi: 10.1146/annurev-psych-010417-085944. Epub 2017 Sep 11. PMID: 28854000.

Leopold DA, Logothetis NK. Multistable phenomena: changing views in perception. Trends Cogn Sci. 1999 Jul;3(7):254-264. doi: 10.1016/s1364-6613(99)01332-7. PMID: 10377540.

M. Schneider, V.G. Kemper, T.C. Emmerling, F. De Martino, & R. Goebel, Columnar clusters in the human motion complex reflect consciously perceived motion axis, Proc. Natl. Acad. Sci. U.S.A. (2019) 116 (11) 5096-5101, https://doi.org/10.1073/pnas.1814504116

Knapen T, Brascamp J, Pearson J, van Ee R, Blake R. The role of frontal and parietal brain areas in bistable perception. J Neurosci. (2011)31(28):10293-301. doi: 10.1523/JNEUROSCI.1727-11.2011.

Deco, G., Sanz Perl, Y., Bocaccio, H. et al. The INSIDEOUT framework provides precise signatures of the balance of intrinsic and extrinsic dynamics in brain states. Commun Biol 5, 572 (2022). https://doi.org/10.1038/s42003-022-03505-7

Kringelbach M.L., Sanz Perl Y, Deco G., Thermodynamics of Mind. Trends in Cognitive Sciences 6, 28 (2024). https://doi.org/10.1016/j.tics.2024.03.009

Sulpizio V, Strappini F, Fattori P, Galati G, Galletti C, Pecchinenda A, Pitzalis S. The human middle temporal cortex responds to both active leg movements and egomotion-compatible visual motion. Brain Struct Funct. (2022) doi: 10.1007/s00429-022-02549-z.