Spatial and temporal integration of binocular disparities in the primate brain

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Context of the thesis

Horizontal binocular disparities
Key ingredients for stereopsis

• Binocular overlap
• Good visual acuity in both eyes
• Accurate coordination between the eyes in all gaze directions
• Ability of the brain to fuse two slightly different retinal images
Key ingredients for stereopsis

• Binocular overlap
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*Horizontal binocular disparities*
Horizontal binocular disparities

Left

Right
Horizontal binocular disparities
Horizontal binocular disparities
Horizontal binocular disparities

- **Left**
- **Right**

**TOP VIEW**

**Uncrossed disparity**
Horizontal binocular disparities

Left

Right

TOP VIEW

Crossed Disparity
Integration of binocular disparities

uncrossed

crossed

Parker, 2007
Integration of binocular disparities

in most visual areas

E.g.: Hubel & Wiesel, 1970; DeAngelis et al., 1998; Janssen et al., 1999; Uka et al., 2000; Taira et al., 2000; Hinkle & Connor, 2001; Tsao et al., 2003; Durand et al., 2009; Likova and Tyler, 2007; Rokers et al., 2009; Sanaka & DeAngelis, 2014; Czuba et al., 2014; Kaestner et al., 2019
Integration of binocular disparities

Temporal gradients

t + t+1

in most visual areas

E.g.: Hubel & Wiesel, 1970; DeAngelis et al., 1998; Janssen et al., 1999; Uka et al., 2000; Taira et al., 2000; Hinkle & Connor, 2001; Tsao et al., 2003; Durand et al., 2009; Likova and Tyler, 2007; Rokers et al., 2009; Sanaka & DeAngelis, 2014; Czuba et al., 2014; Kaestner et al., 2019
Integration of binocular disparities

Spatial gradients

in most visual areas

E.g.: Hubel & Wiesel, 1970; DeAngelis et al., 1998; Janssen et al., 1999; Uka et al., 2000; Taira et al., 2000; Hinkle & Connor, 2001; Tsao et al., 2003; Durand et al., 2009; Likova and Tyler, 2007; Rokers et al., 2009; Sanaka & DeAngelis, 2014; Czuba et al., 2014; Kaestner et al., 2019
Integration of binocular disparities

Temporal gradients

\[ t \rightarrow t+1 \]

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Aims of the thesis

• Temporal integration of binocular disparities
  → Barely studied: Main focus on 2D motion but some differences might exist

• Spatial integration of binocular disparities
  → Influence of natural statistics
  → Link with perception?

Temporal gradients

[Diagram showing temporal gradients with time steps t and t+1]

Spatial gradients

[Diagram showing spatial gradients with an image]
Monkey fMRI
Methodological developments
Monkey fMRI

electrophysiology

fMRI

Homologies

Vanduffel et al., 2001
Monkey fMRI: Development

Macaque conditioning
Experimental setup
Pre-processing and data analysis

[Diagram of experimental setup with labels: Primate chair, Head-post, Coil, Screen, Scanner bore, Reward system, Video projector, Eye-tracker, Reward, Fixation, Time]
The very first study: Optic flow processing

**Original Article**

**Processing of Egomotion-Consistent Optic Flow in the Rhesus Macaque Cortex**

Benoît R. Cottereau$^{1,2}$, Andrew T. Smith$^3$, Samy Rima$^{1,2}$, Denis Fize$^4$, Yseult Héjja-Brichard$^{1,2}$, Luc Renaud$^{5,6}$, Camille Lejards$^{1,2}$, Nathalie Vayssière$^{1,2}$, Yves Trotter$^{1,2}$ and Jean-Baptiste Durand$^{1,2}$

TR = 2s, 1 run = 7 cycles of 16TRs
The very first study: Optic flow processing

ORIGINAL ARTICLE

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Connectivity analyses

De Castro et al., in revision
Stereomotion

Stereomotion processing in the non-human primate brain

2D vs 3D motion

• 2D motion has been widely studied in MT/hMT+
  *Huk & Heeger, 2002; Maunsell & Newton, 1987*

• Much less is known about 3D motion processing
  Most studies focused on MT/hMT+
  *Rokers et al., 2009 (ROI-based analysis)*
  *Sanaka & DeAngelis, 2014; Czuba et al., 2014*

=> Limited understanding of 3D motion despite its ecological relevance
Stereomotion: CDOT processing

Likova & Tyler, 2007
Stereomotion: CDOT processing

→ CSM area in macaque?

Likova & Tyler, 2007

Kolster et al., 2014
Stereomotion: CDOT processing

→ CSM area in macaque?

Likova & Tyler, 2007

Kolster et al., 2014
Experimental paradigm

2 macaques
43 and 47 runs
BOLD signal
Experimental paradigm

Rima et al. (minor revisions)
Projection on the individual surfaces

*Caret software*
Projection on the individual surfaces

*Caret software
Projection overlap

Projection on the F99 template
ROI analyses in the volume

F99

CSM_{STS}  CSM_{ITG}  CSM_{PPC}

M01  M02  M01  M02  M01  M02

0.6  0.5

0.3  0.4

0.2  0.3

0  0.5

PSC  PSC  PSC

CSM  TS  CSM  TS  CSM  TS  CSM  TS
ROI-based analyses

Kolster et al. 2014
ROI-based analyses

Early Visual Areas

MT cluster
MT / V5
V4t
MSTv
FST

M02

V1  V2  V3  V4  V3A

ΔPSC

MT cluster

V4t  MT  MSTv  FST

ΔPSC
Monocular motion sensitivity
Temporal integration?

• Three areas with significant activations for CSM: CSM_{STS}, CSM_{ITG}, CSM_{PPC}
• Tendency observed in the MT cluster (FST, MSTv)
• One area was found to respond exclusively to stereomotion
Temporal integration?

- Three areas with significant activations for CSM: CSM_{STS}, CSM_{ITG}, CSM_{PPC}
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Likova & Tyler 2007
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Likova & Tyler 2007
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Likova & Tyler 2007
Rokers et al., 2009
Kaestner et al. 2019
Spatial Gradients & Natural Statistics

Spatial integration of binocular disparities and orientation biases
Spatial gradients processing

• The brain network responding to spatial gradients is well known in macaques
  
  Janssen et al., 1999, 2000, 2001; Taira et al., 2000; Tsutsui et al., 2002;
  Hinkle & Connor, 2002; Nguyenkin & DeAngelis, 2003

• And so is the involvement of some human areas (V3A, V3B/KO, hMT+, LOC)
  
  Chandrasekaran et al., 2007;
  Murphy, Ban, Welchman, 2013; Ban & Welchman, 2015
Spatial gradients processing

• The brain network responding to spatial gradients is well known in macaques
  

• And so is the involvement of some human areas (V3A, V3B/KO, hMT+, LOC)
  
  Chandrasekaran et al., 2007; Murphy, Ban, Welchman, 2013; Ban & Welchman, 2015

What about an influence of natural statistics within those networks?
Spatial gradients and statistical biases

Sprague et al., 2015
Spatial gradients and statistical biases

Sprague et al., 2015
Spatial gradients and statistical biases

Sprague et al., 2015
Spatial gradients and statistical biases
Visual perception and natural statistics

Are statistical biases reflected at the level of visual perception in macaque?
Measuring corresponding points

Experimental procedure adapted from Cooper E. et al., 2011
Corresponding points location

S1 \( \theta = 4.312^\circ \)

S2 \( \theta = 3.5386^\circ \)
Corresponding points location

Eccentricity (degrees)

Disparity (degrees)

Angle value (degrees)
Corresponding points location

Eccentricity (degrees)

Disparity (degrees)

Angle value (degrees)

M1
\[ \theta = 3.01^\circ \]

S2
\[ \theta = 3.5386^\circ \]
From perception to cortical networks?

Is there an influence of natural statistics within the cortical networks known to process binocular disparities?
Experimental paradigm

2 macaques
BOLD signal
49 runs (26 ‘S’ and 23 ‘T’)
79 runs (33 ‘S’ and 46 ‘T’)

8TRs Blank
8TRs Correlated ‘GS’
8TRs Correlated ‘nGS’
8TRs Uncorrelated ‘U’
Correlated vs. Decorrelated
Orientation biases?
Orientation biases?
Orientation biases?

Rima et al. (minor revisions)

And nothing in M02!
Spatial integration and natural stats?

• Successful adaptation of the experiment to one macaque subject with a tilt reflecting natural statistics

• A cortical network responding to correlated disparities congruent with the literature

• Inconclusive results regarding the possibility of an encoding bias towards more frequent 3D orientations
Discussion

What did we learn about the integration of binocular disparities?
Integration of binocular disparities

Temporal gradients

Spatial gradients

$V1/V2/V3$

$V3A$

$MT/MST/hMT+$

$V4/hV4$

$IT$

$IPS$
Summary of the main results

• Temporal integration of binocular disparities
  • The case of cyclopean stereomotion
    → Human and macaque seem to process CSM in a similar manner

  Likova & Tyler, 2007; Rokers et al., 2009; Kaestner et al.; 2019
Summary of the main results

• Temporal integration of binocular disparities
  • The case of cyclopean stereomotion
    → Human and macaque seem to process CSM in a similar manner
      Likova & Tyler, 2007; Rokers et al., 2009; Kaestner et al.; 2019

• Influence of natural statistics
  • Cortical processing of spatial gradients and 3D orientation biases: Nope! or Nope?
  • Visual perception bias and interspecies comparison
    Cooper and Pettigrew, 1991; Cooper E. et al., 2011
The PIP cluster: An overlap?

Functional dissociation

Stereomotion

Disparity gradients

Héjja-Brichard et al., 2020

Taira et al., 2000;
Tsutsui et al., 2002;
Durand et al., 2007

Retinotopic dissociation

Rima et al., under review
Future directions

• Stereomotion: other cues and fMRI recording
  • A specific role for the area MT?
    *Sanada & DeAngelis, 2014; Czuba et al., 2014; Joo et al., 2016*

• Better understanding of the link between 3D statistics in natural scenes and visual processing
  *Chauhan, Héjja-Brichard, & Cottereau (under review)*
Monkey fMRI
Homologies

Differences
Thank you for your attention!
Appendix
Stimuli: full-field counter phasing (10Hz) checkerboards (40°, 16 sectors) displayed at full contrast, for 4s followed by a 30s blank
One scan = 6 cycles of 34 seconds (total duration: 204s)

<table>
<thead>
<tr>
<th>Subject</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>2.8572</td>
<td>29.9973</td>
<td>0.9267</td>
<td>2.6957</td>
<td>10.0000</td>
</tr>
<tr>
<td>M02</td>
<td>4.7199</td>
<td>24.8772</td>
<td>1.2660</td>
<td>1.3247</td>
<td>6.3917</td>
</tr>
</tbody>
</table>
Results: Projections in the volume
Evolution of polar angle gradients between V3A and LIPvt → robust identification of a succession of gradient reversals → borders shared by those visuotopic areas.

Cf. Arcaro et al., 2011
Horopter: Results

Proportion of rightward motion vs. Line segment separation (degrees)

- Ecc = -0.7
- Ecc = -0.3
- Ecc = -0.1
- Ecc = 0
- Ecc = 1
- Ecc = 3
- Ecc = 7

PSE values indicated for each condition.
Results for 8 human observers

Eccentricity (degrees) vs. Disparity (degrees) for each observer:

- S1 $\theta = 3.927^\circ$
- S2 $\theta = 3.538^\circ$
- S3 $\theta = 7.178^\circ$
- S4 $\theta = 5.712^\circ$
- S5 $\theta = 4.312^\circ$
- S6 $\theta = 4.015^\circ$
- S7 $\theta = 2.620^\circ$
- S8 $\theta = 5.210^\circ$
Horopter: Observers’ characteristics

Optimal shear angle \( \vartheta = 2 \tan^{-1} \frac{I}{2h} \)

<table>
<thead>
<tr>
<th>Subject</th>
<th>IOD (cm)</th>
<th>Eyes height (cm)</th>
<th>Optimal shear angle (degrees)</th>
<th>Shear angle all sessions (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>6.15</td>
<td>153.0</td>
<td>2.3028</td>
<td>3.927</td>
</tr>
<tr>
<td>S2</td>
<td>6.30</td>
<td>171.5</td>
<td>2.1045</td>
<td>3.5386</td>
</tr>
<tr>
<td>S3</td>
<td>6.55</td>
<td>166.5</td>
<td>2.2537</td>
<td>7.1776</td>
</tr>
<tr>
<td>S4</td>
<td>6.15</td>
<td>157.5</td>
<td>2.237</td>
<td>5.7120</td>
</tr>
<tr>
<td>S5</td>
<td>6.70</td>
<td>169.5</td>
<td>2.2645</td>
<td>4.3118</td>
</tr>
<tr>
<td>S6</td>
<td>6.90</td>
<td>163.5</td>
<td>2.4176</td>
<td>4.0147</td>
</tr>
<tr>
<td>S7</td>
<td>6.03</td>
<td>156.0</td>
<td>2.2144</td>
<td>2.6200</td>
</tr>
<tr>
<td>S8</td>
<td>6.30</td>
<td>169.0</td>
<td>2.1356</td>
<td>5.2106</td>
</tr>
<tr>
<td>M1</td>
<td>3.14</td>
<td>38</td>
<td>4.8973</td>
<td>3.01</td>
</tr>
</tbody>
</table>
Selectivity profile along the STS