Retinotopic organization and functional subdivisions of the human lateral geniculate nucleus and superior colliculus

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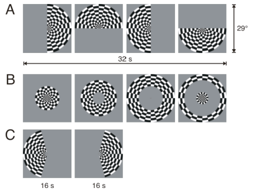
Overview

The lateral geniculate nucleus (LGN) of the thalamus and the superior colliculus (SC) have been well studied in other primates, but the study of their organization and function in humans has been largely limited to lesion and post-mortem analyses. Here we show that the retinotopic structure of the LGN, including its eccentricity and polar angle magnification factors, can be measured with a 3T MRI scanner and a high-resolution imaging sequence (1.5 × 1.5 × 2 mm voxel size). Sensitivity to stimulus contrast varied throughout the extent of the LGN, and based on this, we attempted to distinguish the magnocellular and parvocellular divisions. In the SC, contralateral activation was observed, but unlike in the LGN, contrast sensitivity was uniform throughout its extent.

Stimuli

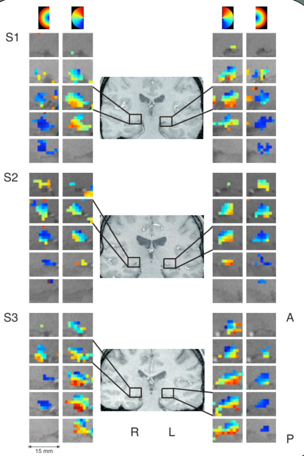


A. Rotating hemifield stimulus used to map polar angle.
B. Expanding ring stimulus used to map eccentricity.
C. Alternating hemifield stimulus used to measure contrast sensitivity.

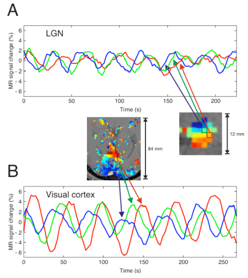
Methods

MRI Procedures: Images were acquired using a 3T Siemens Allegra head-only scanner with a birdcage head coil. 18 interleaved coronal slices (2 mm thick, no gap) were acquired with a standard EPI sequence (TR=2 s, TE=41 ms, FA=90°), 192 mm FOV and 128 x 128 matrix (1.5 × 1.5 × 2 mm voxel resolution). The most posterior slice was aligned with the posterior edge of the corpus collosum. Observers were scanned in three separate sessions, one for each stimulus type (A–C above).
Stimuli: Observers maintained fixation while passively viewing the checkerboard patterns that were presented at the mean background intensity and reversed contrast at 8 Hz. The 100% contrast eccentricity (A) and polar angle (B) stimuli smoothly swept through the visual field while the localizer stimuli (C) were presented discretely to alternating hemifields at either 100% or 10% contrast in different scanning runs. 8 stimulus cycles were presented per scan.
Analysis: The images were registered to correct for motion and scanner drift but were not processed further. 6–12 scanning runs of 128 time points each were averaged, and a Fourier analysis was performed on the last 7 stimulus cycles to calculate the phase, amplitude and correlation components of each voxel's response. Responses were thresholded at $r \geq .25$ ($p < .0038$).

LGN retinotopic maps

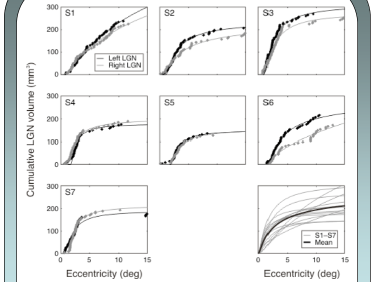


Spatial specificity



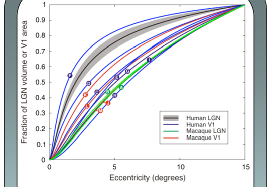
A. Time series of three individual voxels in the LGN. The signals from the adjacent voxels exhibited distinct phases.
B. Time series of identically-sized voxels in the visual cortex.

Eccentricity magnification factor



The integral of a magnification power law function was fit to the cumulative volume measurements of the left and right LGNs in each individual subject. These functions and the group average are plotted in the lower right panel.

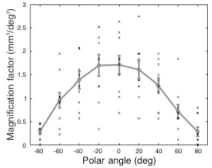
Magnification comparison



The representation of the fovea in the human LGN is expanded relative to that in the macaque LGN or V1. References:

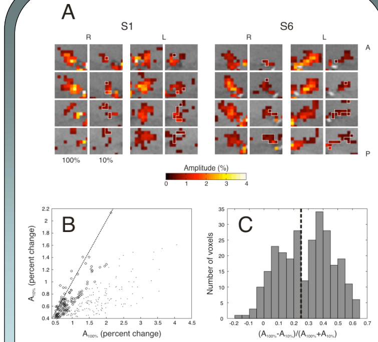
A. Malpeli and Baker, 1975; Malpeli et al., 1996
B. Connolly and Van Essen, 1984; Malpeli and Baker, 1975; Schein and de Monasterio, 1987
C. Duncan and Boynton, 2003
D. Slotnick et al., 2001
E. Engel et al., 1997
F. Sereno et al., 1995
G. Grüsser, 1995
H. Engel et al., 1994
I. Brindley and Lewin, 1968a; Cowey and Rolls, 1974; Grüsser, 1995
J. Tootell et al., 1988; Wässle et al., 1990
K. Van Essen et al., 1984
L. Tootell et al., 1982
M. Hubel and Freeman, 1977; Hubel and Wiesel, 1974

Polar angle magnification



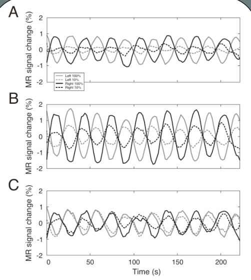
In the human LGN, the horizontal meridian (0°) is substantially overrepresented relative to the vertical meridian (±90°). Partial volume effects may have somewhat exaggerated these measurements (the vertical meridian is represented on the edges of the LGN while the horizontal meridian is interior). However, the observed effect is expected to some degree since the horizontal meridian is overrepresented in the human retina (Perry and Cowey, 1985; Stone and Johnston, 1981), the macaque visual cortex (Van Essen et al., 1984) and the macaque LGN (Connolly and Van Essen, 1984).

LGN contrast response



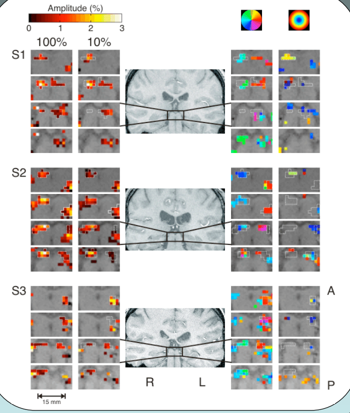
A. Amplitudes in response to the 100% (left column of pair) and 10% (right column) stimuli are shown for the right (R) and left (L) LGN in two typical subjects. White outlines border voxels that exhibited weak contrast modulation, CMI < .25.
B. For each voxel responsive to the 10% stimulus, the amplitudes in response to the 100% ($A_{100\%}$) and 10% ($A_{10\%}$) stimuli are plotted. Open circles: CMI < .25.
C. Histogram of the contrast modulation index CMI = $(A_{100\%}-A_{10\%})/(A_{100\%}+A_{10\%})$.

Mean LGN time series

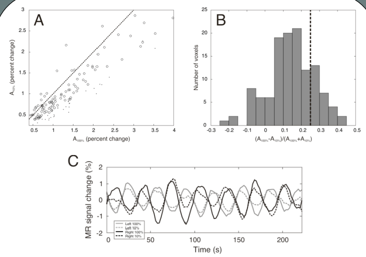


A. Voxels (across subjects) unresponsive to 10% stimulus
B. Voxels responsive to 10% contrast stimulus that exhibited a large amplitude increase in response to the 100% stimulus: CMI = $(A_{100\%}-A_{10\%})/(A_{100\%}+A_{10\%}) \geq .25$.
C. Voxels responsive to 10% stimulus and with CMI < .25.

Superior colliculus



SC contrast response



A. For each voxel responsive to the 10% stimulus, the amplitudes are plotted in response to the 100% ($A_{100\%}$) and 10% ($A_{10\%}$) stimulus. Open circles: CMI < .25.
B. Histogram of the contrast modulation index CMI = $(A_{100\%}-A_{10\%})/(A_{100\%}+A_{10\%})$.
C. Mean time series of all SC voxels across all subjects.