**Supplementary Data/Discussion**

Spatially Distributed Encoding of Covert Attentional Shifts in Human Thalamus

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**Supplemental Data**

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Section 1 Axial and sagittal statistical parametric maps of whole thalamus

Please refer to Figures S1 – S4, available for separate download.

The figures display serial axial, or sagittal, slices showing position specific BOLD activity superimposed on structural images from each subject, CG, WY and HE. The stimulus test position diagrams P1 (Figs S1 & S3) and P2 (Figs S2 & S4) show two trios of test positions (red, green and blue), P2 being rotated one position clockwise from P1. Red, green and blue voxels indicate significant effects of attentional shifts to one of these three positions. The colour mixing scheme shows how voxels responsive to two positions are represented by duller yellow, magenta and cyan hues, whilst responses to all three are rendered in darker neutral shades (black in most instances). The thalamus of each subject was sliced at levels comparable to those illustrated in the Morel atlas*, as shown in the centre panels of each Figure.

Figure S1  Axial slices detailing response to test triplet positions P1.

Figure S2  Axial slices detailing response to test triplet positions P2.

Figure S3  Sagittal slices detailing response to test triplet positions P1.

Figure S4  Sagittal slices detailing response to test triplet positions P2.

* Morel A, Magnin M, Jeanmonod D. 1997. Multiarchitectonic and stereotactic atlas of the human thalamus. J Comp Neurol. 387:588-630. Reproduction of atlas sections by permission of John Wiley & Sons Inc.
Section 2A: Stimulus selectivity profiles (SSPs)

The lack of spatially specific responses to visual stimuli (i.e. the circular array of target and distractor discs) is confirmed by the analysis of stimulus selectivity profiles (SSPs), calculated by the same Bayesian distribution fitting procedure used to provide attentional selectivity profiles (ASPs) of individual voxels in the main text. We derived SSPs for the unilaterally active cluster in dorsal pulvinar (DPC). All voxels displayed a flat SSP – i.e. zero modes – consistent with the absence of a significant response to any position (Figure S5).

![Figure S5](image)

**Figure S5** Distribution fitting for Stimulus Selectivity profiles in DPC: Histogram plots show the number of voxels within the DPC whose SSPs are best fit by a particular number of modes. The ROI for each was a 314 voxel sphere (~9mm diameter) centred on the centre of mass of the unilateral clusters of interest shown in Figure 4 of the main paper for subjects HE and WY, at matching locations in the opposite right hemisphere of these subjects, and at bilateral matching locations in CG (given the absence of an equivalent focus of activation on which to anchor the ROI).

Section 2B: Comparison of attentional and stimulus selectivity profiles across different nuclei

We performed the same distribution fitting protocol to obtain the ASPs and SSPs in two other nuclei identified to be active in all hemispheres - mediodorsal (MD) and parafascicular (Pf). The volume of the ROI in each case was tailored to the cluster size in each nucleus/hemisphere. Figure S6 compares histograms for number of peaks in the ASP; Figure S7 provides a similar treatment for the SSP. Whilst the SSPs are uniformly flat (i.e. zero peaks), there are consistent differences between nuclei in the mean numbers of peaks in the ASPs. Activated voxels in the unilateral DPC showed a significantly greater mean number of peaks than ipsilateral Pf and MD, and Pf, in turn, showed a greater number of peaks than MD – a finding common to both hemispheres in all three subjects, as documented in Table S1.
**Figure S6**  Attentional Selectivity Profiles: Histogram plots show the number of voxels within each nucleus whose ASPs are best fit by a particular number of modes. Row one = left parafascicular nucleus; row two = right parafascicular; row three = left mediodorsal nucleus; row four = right mediodorsal nucleus.

**Figure S7**  Stimulus Selectivity Profiles: Histogram plots show the number of voxels within each nucleus whose SSPs are best fit by a particular number of modes. Row one = left parafascicular nucleus; row two = right parafascicular; row three = left mediodorsal nucleus; row four = right mediodorsal nucleus.
Table S1: Comparison of multi-peaked ASPs in dorsal pulvinar cluster (DPC), and in mediodorsal (MD) and parafascicular (Pf) nuclei, using a Mann-Whitney U test with correction for tied ranks. The table lists the mean number of peaks per voxel in 3 nuclei, and significant differences (*) in the mean number of peaks per voxel between these nuclei. Voxels submitted to this analysis were those that showed significant effects for one or more of the 16 attentional directions tested (F-test, p<0.05 FWE).

|       | HE left | WY left | CG left | HE right | WY right | CG right |
|-------|---------|---------|---------|----------|----------|----------|
| **DPC** mean no. peaks no. of voxels | 2.31 284 | 2.39 215 | N/a | N/a | N/a | N/a |
| **Pf** mean no. peaks no. of voxels | 2.08 99 | 1.97 38 | 2.06 355 | 2.17 330 | 1.78 46 | 1.98 102 |
| **MD** mean no. peaks no. of voxels | 1.31 108 | 1.47 197 | 1.51 194 | 1.35 114 | 1.53 73 | 1.73 41 |
| **MW-test: DPC vs. Pf** P value (2-tail) | * 0.036 | * 0.012 | N/a | N/a | N/a | N/a |
| **MW-test: DPC vs. MD** P value (2-tail) | * < 1.0E-16 | * < 1.0E-16 | N/a | N/a | N/a | N/a |
| **MW-test: Pf vs. MD** P value (2-tail) | * 8.4E-12 | * 0.0017 | * 4.1E-12 | * 2.2E-16 | 0.068 | 0.095 |

Finally, equivalent to our treatment of DPC, we constructed polar plots of directional sensitivity by pooling ASP peaks across all voxels in an active cluster (Figure S8). Similar to DPC, these plots show no gross directional bias in MD and Pf nuclei for upper vs. lower, or left vs. right positions ($t_{(14)} < 2.14$, $P > 0.05$).

**Figure S8** Polar plot of frequency of peak positions for the each cluster of interest. These plots have been arbitrarily scaled for cross comparison of angular distribution for the different nuclei.
The Nuclear Profile of Thalamic Activity

Section 3A: Template fitting and nuclear scoring: further examples

Figure S9 Individual variation in nuclear anatomy of thalamus.

Template HB1R (top) is from the horizontal series used in the thalamic atlas of Morel et al (1997). Templates HB2R and HB5L are from two separate series at the same level, to illustrate variability in the outline of the thalamus and in the internal nuclear conformation. In the superimpositions (below), HB1R is shown in greyscale and HB2R and HB5L in bold outline with nuclear labels.

[Atlas sections in Figs S9 & S10 redrawn from Morel et al (1997) with permission of John Wiley & Sons Inc.]
Figure S10  Reliability of nuclear profiling using different anatomical templates. Images of left and right thalamus from one subject (CG) are superimposed with alternative templates (HB1R, HB2R & HB5L as shown in Fig.S9) from the atlas of Morel et al (1997). Each template is distorted to match the outline of thalamic grey matter, affording a comparison of the inferred profiles of nuclear activity.
Table S2 Nuclear Profiling: activation scores for example shown in Fig. S10

|       | Li | Po | PuL | PuM | PuA | CM | Pf | VPLp | VPM | VPMPc | CeM | VM |
|-------|----|----|-----|-----|-----|----|----|------|-----|-------|-----|----|
| HB1R  | L  | -  | ++  | ++  | ++  | (+) | ++ | ++   | -   | ++    | (+) | (+) |
| HB2R  | L  | -  | ++  | ++  | ++  | (+) | ++ | ++   | -   | ++    | (+) | -  |
| HB5L  | L  | -  | (+) | (+) | ++  | ++  | ++ | ++   | -   | ++    | -   | -  |
| HB1R  | R  | ++ | ++  | -   | ++  | ++  | -  | (+)  | ++  | -     | -   | -  |
| HB2R  | R  | (+) | ++ | -   | ++  | ++  | -  | (+)  | (+) | -     | -   | -  |
| HB5L  | R  | ++ | ++  | -   | ++  | ++  | -  | -    | ++  | -     | -   | -  |

Key: active & inactive nuclei denoted by ++ & -; (+) denote nuclei enclosing an active zone of between 1 and 2.5 voxels.

Figure S9 compares the nuclear configuration of horizontal sections from three different brains at level DV0 (the level of the standard ac-pc plane), taken from the human thalamus atlas of Morel et al (1997). Much the same nuclei are present in much the same arrangement, but with varying degrees of overlap stereotaxically. As an empirical exercise, to gauge the impact of anatomical variability on our nuclear scoring system, Figure S10 shows each of these templates deformed to match the outline of left and right thalamus from one of our subjects (CG). Although the nuclear outlines of the reference MR section are unknown, we assume that the lack of fit between template and reference section nuclei will be similar to the lack of fit across templates. The outcome, as summarised in Table S2, is that there is a good level of consistency between the alternative nuclear profiles of activity derived from these three different templates. To facilitate this assessment, Table S2 uses a 3-way classification: active or inactive (++ or -), and an intermediate grade denoted by (+) entries, where the active territory enclosed within the superimposed nuclear outline has an area of at least 1, but less than 3 voxel units. Considering left and right hemispheres separately, all the discrepancies in Table S2 are either between - and (+), or between (+) and ++ entries.

A simpler binary scoring system (+/-) was used for the systematic nuclear activation profile of each subject, discussed in the main text and shown in full in Table S3. Instances of ‘minor’ activation, such as the (+) entries in Table S2, were scored as inactive, unless there was a corresponding major (+++) activation at a similar nuclear location in either of the adjacent atlas levels. Thus, a minor activation occurring at an isolated, single level would not generate an entry in Table S3.

The above criterion for crediting a score to a particular nucleus was separate and in addition to our criterion for discounting small clusters, that combined a conjunction test and a size test: non-scoring clusters were those showing a single positional specificity for a shift in spatial attention, and failing to achieve a minimum dimension of at least three voxels in all three axes (i.e. both within and orthogonal to the plane of inspection).
### Section 3B: Profile of thalamic nuclear activation - full tabulation

|       | TOT | CG  | WY  | HE  | L  | R  |
|-------|-----|-----|-----|-----|----|----|
| CL    | 6   | 2   | 2   | 2   | 3  | 3  |
| MDpc  | 6   | 2   | 2   | 2   | 3  | 3  |
| PuM   | 6   | 2   | 2   | 2   | 3  | 3  |
| Sg    | 6   | 2   | 2   | 2   | 3  | 3  |
| MDpl  | 5.5 | 2   | 1.5 | 2   | 2.5| 3  |
| Pf    | 5.5 | 1.5 | 2   | 2   | 2.5| 3  |
| MGN   | 5   | 2   | 1   | 2   | 2  | 3  |
| Vlp   | 5   | 1.5 | 2.5 | 2.5 |    |    |
| CM    | 4.5 | 1.5 | 1.5 | 2.5 | 2  |    |
| Po    | 4.5 | 2   | 1   | 1.5 | 1.5| 3  |
| sPf   | 4.5 | 1.5 | 1   | 2   | 2.5| 2  |
| Li    | 4   | 1   | 2   | 2   | 2  |    |
| LP    | 4   | 1   | 2   | 1   | 1.5| 2.5|
| VA    | 4   | 0.5 | 2   | 1.5 | 2  | 2  |
| VPL   | 4   | 1   | 2   | 1   | 1.5| 2.5|
| VPMpc | 4   | 1   | 1   | 2   | 2  | 2  |

|       | VM  | 3.5 | 1   | 0.5 | 2  | 2  | 1.5 |
|-------|-----|-----|-----|-----|----|----|-----|
| PuA   | 3   | 1.5 | 0.5 | 1   | 1.5| 1.5| 1.5 |
| PuL** | 3   | 1   | 1   | 1   | 1  | 1  | 2   |
| Vla   | 3   | 0.5 | 1.5 | 1   | 2  | 1  |     |
| CeM   | 2.5 | 0.5 | 0.5 | 1.5 | 1  |    |     |
| VPI   | 2.5 | 1   | 0   | 0.5 |    |    | 2   |
| VPM   | 2   | 1   | 0.5 | 0.5 | 1.5|    |     |
| MV    | 2   | 0   | 0   | 0   | 0  | 1  | 1   |
| VAmc  | 1   | 0   | 0.5 | 0.5 | 0  | 0  | 0.5 |
| Hb    | 1   | 0   | 0   | 1   | 0  | 0  | 1   |
| LD    | 1   | 0   | 0   | 0   | 1  | 0  | 0   |
| MTT   | 0.5 | 0   | 0.5 | 0   | 0  | 0  | 0   |
| AD    | 0   | 0   | 0   | 0   | 0  | 0  | 0   |
| AM    | 0   | 0   | 0   | 0   | 0  | 0  | 0   |
| AV    | 0   | 0   | 0   | 0   | 0  | 0  | 0   |
| MDmc  | 0   | 0   | 0   | 0   | 0  | 0  | 0   |
| R     | 0   | 0   | 0   | 0   | 0  | 0  | 0   |
| ZI    | 0   | 0   | 0   | 0   | 0  | 0  | 0   |

**Table S3: Nuclear profile of thalamic activity:** Subjective scores for the activation of specific thalamic nuclei. Analysing a single anatomical plane, a score of 0.5 is awarded to a nucleus if there is at least one level at which it coincides with a focus of activity, elicited by at least one test position. A qualifying focus consists of a minimum 3 contiguous voxels. The analysis is independently replicated across two planes of section, in each of six hemispheres, to yield a maximum score of 6. Subsequent columns (CG, WY & HE) report the sub-scores for each subject, pooled across hemispheres, and the sub-scores for each hemisphere (L, R) pooled across subjects. The scores are compiled from analysis of a subset of 6 out of the 16 positions tested, (i.e. the test positions whose outcome is shown in Figs. S1-S4).

- **CL** central lateral nucleus
- **MDpc** mediodorsal nucleus, parvocellular dvn.
- **PuM** medial pulvinar
- **Sg** * suprageniculate nucleus
- **MDpl** mediodorsal nucleus, paralamellar dvn.
- **Pf** parafascicular nucleus
- **MGN** * medial geniculate nucleus
- **Vlp** ventral lateral posterior nucleus
- **CM** centre median nucleus
- **Po** posterior nucleus
- **sPf** subparafascicular nucleus
- **Li** limitans nucleus
- **LP** lateral posterior nucleus
- **PuL** * lateral pulvinar
- **VA** ventral anterior nucleus
- **VM** ventral medial nucleus
- **VPL** ventral posterior lateral nucleus
- **VPMpc** ventral posterior medial nucleus, parvocellular division
- **PuA** anterior pulvinar
- **VLa** ventral lateral anterior nucleus
- **CeM** central medial nucleus
- **VPI** ventral posterior inferior nucleus
- **VPM** ventral posterior medial nucleus
- **MV** medioventral nucleus
- **VAmc** ventral anterior nucleus, magnocellular division
- **Hb** habenular nucleus
- **LD** lateral dorsal nucleus
- **MTT** mammillothalamic tract
- **AD** anterodorsal nucleus
- **AM** anteromedial nucleus
- **AV** anteroventral nucleus
- **MDmc** mediodorsal nucleus, magnocellular dvn.
- **R** reticular thalamic nucleus
- **ZI** zona incerta

* * absent in horizontal series, sagittal score doubled
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Note on terminology & inclusion criteria. For purposes of standardisation, we adopt without modification the terms and abbreviations exactly as listed in the Morel atlas. These are derived from the account of human thalamus given by Hirai & Jones (1989), which in turn adapted terminology from the thalamic atlas of Macaca mulatta of Olszewski (1952), with the explicit intention of standardising anatomical concepts of the structure of the thalamus in primates. Table S3 includes all thalamic nuclei that appear in both the horizontal and sagittal series of the Morel atlas, including inactive nuclei, plus SG, MGN and PuL that were active but outside the range of one series. For three nuclei (MGN, VLp & VPL) subdivisions listed in the atlas are amalgamated to form a single entry. The excluded thalamic nuclei are LGN and PuI: of these, only PuI may have been active (see note below).

Section 3C: Atlas anomalies

Overall, we have every confidence that the Morel atlas provides an effective and reliable means of identifying the thalamic nuclei most likely to correspond to any set of active voxel clusters. Nonetheless, there are a number of minor issues that deserve an added note of explanation.

Limits of horizontal and sagittal series.
A few foci of activation were situated outside the range covered by a particular atlas series. For example, there was a substantial, cross-subject focus of activity centred around the location of the MGN and Sg, but these nuclei are situated below the level of the most ventral section (V1.8) in the horizontal series. Therefore these nuclei could only be scored within the sagittal series. Similarly, because PuL (lateral pulvinar) is only marked in the most lateral section of the sagittal series, PuL activation was scored only within the horizontal series. For comparability, the score obtained for these nuclei (MGN, Sg & PuL) was doubled for entry into Table S3.

Mislabelling of inferior pulvinar (PuI) ?
We suspect there is one instance of a typographical error in the horizontal atlas series, where in section V1.8 the structure labelled PuL is probably, in reality, PuL (i.e. inferior not lateral pulvinar). Taking into account all three atlas series, PuL (inferior pulvinar) is marked only in the most posterior section of the coronal series (P1.8), where it sits ventral to PuL with a dorsal extremity verging on level DV0 (i.e. the ac-pc plane). There is thus good reason to suppose that PuL in horizontal sections V1.8, and perhaps V0.9, might be relabelled as PuL, for sections at these levels would intersect with PuL, not PuL, as shown in the coronal section. Had we applied this correction, PuL would have appeared toward the foot of Table S3, stealing some of the score from PuL. But although the correction seems likely, it is not axiomatic, given that left and right thalami are not necessarily identical. Refer to next item.

Left / Right asymmetries
The horizontal and sagittal series in the Morel atlas are taken from opposite hemispheres of the same brain. Thus they have a high degree of structural uniformity, but are by no means exact replicas of each other. The linear distortion is less than 7% in all three axes, as estimated by a centre of gravity analysis of 13 selected nuclei (Niemann et al. 2000). We have not attempted a systematic analysis, but can offer the following examples of discrepancies in nuclear boundaries by way of illustration.
**Mediodorsal nucleus, paralamellar division:** MDpl is marked on just two sagittal sections, L9.9 and L10.8. By contrast, MDpl spans a mediolateral range of up to 5mm in the horizontal series, e.g. as depicted in the sections at D7.2 and D8.1 where the medial limit of the (dashed) nuclear boundary is 9mm from the midline and the lateral limit is 14mm from the midline.

**Central lateral nucleus:** CL wraps around MDpc and MDpl, and appears in every sagittal section from the midline as far as level L 13.5, but not beyond this lateral limit; in the horizontal series CL extends up to 16 mm laterally from the midline, e.g. as drawn in the section at level D 7.2.

**Ventral posterior lateral nucleus:** VPL is marked in the most ventral horizontal sections, and continues dorsally up to level D 7.2; by contrast, VPL extends dorsally to 10mm above the ac-pc plane in several sagittal sections, having a maximum dorsal limit of 13mm superior to ac-pc as depicted in sagittal section L12.6.

It is not unexpected that the two separate thalamic atlas series might deliver different verdicts as to the identity of voxel clusters at certain critical locations. By collating the ‘opinions’ of two series, and according each an equal weight, we aim to have achieved a mild reduction of miscreant nuclear identifications.

**Section 3D: Fractional Volumetric Activation (FVA) as a quantitative estimate of relative nuclear activation**

The procedure for estimating FVAs provided a simple tool to examine the relative degree of activation amongst thalamic nuclei, serving as a useful counterpoint to the reliability of activation data listed in Table S3. The source data, the fraction of levels at which each nucleus was scored for activation, in each of the horizontal and sagittal series of the atlas, was generated in the survey of activity underlying Table S3. We report the product of these fractions, adjusted to estimate the fractional volume of activation (FVA) for each nucleus. If, for example, a spherical cluster of active voxels coinciding with a particular nucleus were to occupy 50% of the levels in which that nucleus occurs in the horizontal series, and (by chance) a similar proportion of both the sagittal and coronal series, we can estimate the fractional volume of activation (FVA) in that nucleus at 12.5% (i.e. 0.5^3). As we did not perform an atlas comparison in the coronal plane, we report the joint horizontal and sagittal occupancy data as (hs)^1.5 (where h and s are the respective horizontal and sagittal fractions of active levels), in order to approximate a 3D estimate of the FVA. For three nuclei that the atlas only allowed to be scored in one plane of section, the FVA was estimated by h^3 or s^3.

As noted in the main text, the actual values of FVA obtained should be treated cautiously, given that the number of ‘active’ voxels is critically contingent on an arbitrary statistical threshold. Hence it is the relative value of FVA across nuclei that is of primary consideration. The relative values of FVA for each nucleus are unbiased if all clusters of active voxels are blob-like – i.e. roughly spherical. If one axis of the cluster is relatively extended, it will tend to magnify the FVA, the more so if the long axis of the cluster is not aligned with any of the cardinal anatomical axes (horizontal, sagittal, coronal), such that it crosses more levels in all planes. However there is no reason to suspect any systematic effect in favour of any given nucleus once the FVA data are collated across all six hemispheres. A second consideration is the presence of two or more voxel clusters within some of the larger nuclei. Similar to the above, the relative enlargement of the FVA estimate will be greater if pairs of clusters do not align along any cardinal axis. Several of the larger nuclei,
such as PuM, MDpc and VLp (medial pulvinar, parvocellular division of mediodorsal & ventral lateral posterior nuclei) do indeed possess multiple clusters in some hemispheres. However, as the major distinction between the qualitative assessment of activation (Table S3) and the semi-quantitative measure (FVA – Fig. 8 & Fig. S11) was a reduction in the relative prominence of PuM and VLp in the latter, there is no sign that any systematic bias in the FVA estimates has affected our conclusions. In terms of relative volume, some smaller nuclei, such as Pf, MDpl, Sg and MGN would appear to be the most intensely activated (as illustrated in Figure 8 of the main text).

Figure S11: Comparison of fractional volumetric activation in left and right hemispheres, for the same nuclei illustrated in Fig. 8 (main text), here ordered by L:R ratio. (MGN* & Sg*: FVA estimates derived from sagittal plane alone).

Figure S11 shows details of right-left variation for the same thirteen nuclei shown in Fig. 8, again from pooled subject data. The thalamic nuclei are ordered by the relative FVA scores between hemispheres, and demonstrate regional variation across the thalamus in relative activity between right and left hemispheres. Specifically, the caudal intralaminar nuclei (Pf, sPf & CM) display left hemisphere dominance, and the posterior group (MGN, Po, Sg & VPI), right hemisphere dominance. Activation of the remaining nuclei is more balanced bilaterally.
Section 3E  Comparison to anatomical organisation of nonhuman primate corticothalamic circuitry

Note on pulvinar terminology, and human – macaque homology
The pulvinar subdivisions marked in the Morel atlas are the traditional ones, based on standard myelo- and cytoarchitectonic criteria originally derived from macaques (Olszewski 1952). However these boundaries are of questionable functional significance (Shipp 2003), and a re-parcellation of the pulvinar driven by histochemical observations has been proposed (Gray et al. 1999; Gutierrez et al. 2000; Gutierrez et al. 1995; Stepniewska and Kaas 1997). In brief, the ventral portion of the macaque pulvinar is occupied by several histochemically defined subzones of the inferior pulvinar (PuI); overall, however, the histochemical PuI is larger than the traditional PuI defined by standard myelo- and cytoarchitectonic criteria (Olszewski 1952). The histochemical PuI amalgamates traditional PuI with the ventral half of traditional lateral pulvinar (PuL), and the amalgamation can be referred to as ventral pulvinar; dorsal pulvinar incorporates the dorsal part of PuL with the traditional medial pulvinar. Human thalamus shows a very similar pattern of histochemical subzones within PuI, suggesting that this revised terminology does generalise to anthropoid primates (Cola et al. 1999; Cola et al. 2005).

To supplement myelo- and cytoarchitectonic criteria in delineating human thalamic nuclei, Morel et al. (1997) referred to histochemical material using calcium binding proteins (parvalbumin, calbindin and calretilin), but not acetylcholinesterase staining which forms an important component of the histochemical re-parcellation of primate pulvinar. The resulting gross topology of human PuM, PuL and PuI is thus not too dissimilar from that illustrated by Olszewski (1952) for macaques, although, in comparing the two species, it has been remarked elsewhere that the medial nucleus of the human pulvinar is relatively enlarged and rotated ventrally down the posterior surface of the thalamus (Hirai and Jones 1989). Because the Morel atlas provides a standard point of reference we retain its terms in describing the primary anatomical location of active foci in our study, touching on the histochemical structural revisions where reaching toward functional considerations.

Comparison to cortico-thalamic connectivity in nonhuman primate: thalamic connections of cortical eye fields
There is considerable evidence to the effect that the cortical neural mechanisms regulating covert attention overlap with the oculomotor system. There are several cortical sites, known as ‘eye fields’, where electrical microstimulation produces eye movements (Lynch and Tian 2005). Here we review how the eye fields’ documented connectivity with the thalamus in nonhuman primates compares to the patterns of activation elicited in human thalamus by our covert attention task. Whilst the organisation of human cortico-thalamic connectivity will not be an exact, scaled-up replica of the macaque system, the anatomy of the thalami of both species is known to be highly comparable (e.g. as noted above), and there is some existing evidence demonstrating homology of the major cortico-thalamic systems (Behrens et al. 2003; Johansen-Berg et al. 2005).

It is notable that seven of the eight top-scoring nuclei identified in Table S3 are all known to be connected with the frontal eye field (FEF). We concentrate on a trio of studies that used electrophysiological identification of FEF prior to injection of tracers, and which report concordant results (Huerta et al. 1986; Stanton et al. 1988; Tian and Lynch 1997). In general, the FEF is reciprocally connected to a longitudinal zone tracing the internal medullary lamina (IML) and adjacent nuclei. Perhaps the strongest connections involve the paralamellar part of the mediodorsal nucleus (MDpl), also known as the pars multiformis
One study (Stanton et al. 1988) distinguished between parts of FEF eliciting small or large saccades (sFEF & lFEF), and noted differential connectivity with MDpc and MDpl, sFEF being more closely linked to the latter. In this study one sFEF case [case ‘TRB’, (Stanton et al. 1988)] involved a site in FEF eliciting saccades of 2°, and is thus particularly appropriate for comparison to our study, where the covert shifts were of 3°: it revealed outputs from sFEF to VAmc (ventral anterior nucleus, magnocellular part), MDmf, MDpc, ‘area X’ (a medial sector of ventrolateral nucleus, equivalent to VLp in Table S3), PuM, parafascicular and the suprageniculate/limitans nuclei. All of these nuclei are listed in Table S3 and only one of them (VA) has a relatively low (middle-ranking) score. Anterograde tracer within the central lateral nucleus (CL) i.e. the part of the IML surrounding MD – was thought to represent fibres of passage, rather than actual terminations in CL (Stanton et al. 1988). However CL is known to be a source of output to FEF (Huerta et al. 1986; Tian and Lynch 1997). The other thalamic nuclei are all connected bi-directionally with FEF, apart from the parafascicular nucleus, which receives significant FEF input whilst making a nugatory return projection (Huerta et al. 1986; Tian and Lynch 1997). The thalamic connections of the supplementary eye field (SEF), located in medial frontal cortex, are very similar to FEF (Huerta and Kaas 1990; Shook et al. 1991). Between them, the two SEF reports list reciprocal connections with all the same nuclei mentioned above, with some variation in the relative strengths.

The parietal eye field (PEF) of macaque monkeys is equivalent to area LIP, since it is LIP, rather than 7A (or any other inferior parietal area), that communicates with the oculomotor layers of the superior colliculus (Lynch et al. 1985). However the two areas make comparable sets of thalamic connections, and area 7A also has pronounced spatial-attention related characteristics (Bender and Youakim 2001; Mountcastle et al. 1987; Quraishi et al. 2007) including suppression of response to attended stimuli (Robinson et al. 1995; Steinmetz et al. 1994). The thalamic connections of posterior parietal cortex are concentrated upon the dorsal pulvinar, with subsidiary involvement of several other nuclei that share input from the FEF, such as VA, VL and SG/Li (Asanuma et al. 1985; Hardy and Lynch 1992; Schmahmann and Pandya 1990; Weber and Yin 1984; Yeterian and Pandya 1985). However the MD nucleus, the primary target of FEF output to thalamus, is only occasionally reported as a minor site of output for posterior parietal cortex (depending on the exact site, and size of tracer deposition). Also the parafascicular nucleus, another reliable site of FEF input, does not appear to make similar connections with the posterior parietal cortex. Of further note is a specific subset of thalamic connections made by a vestibular-related subregion of area 7, located in the dorsal bank of the superior temporal sulcus. Specifically, these are connections with the magnocellular MGN, the ventral posterior inferior nucleus (VPI), and CL (Faugier-Grimaud and Ventre 1989). These nuclei score respectably in Table S3 (5.0, 2.5 and 6.0 respectively), raising the possibility that the covert task recruits vestibular mechanisms (- at least when performed from a horizontal posture within the scanner).

A large unilateral focus of activity, termed ‘DPC’ in the main text, occurred in the dorsal pulvinar of the left thalamus in two subjects (also spreading into the adjacent lateral posterior nucleus, LP); we refer to ‘dorsal’ pulvinar as a provisional functional subunit of human pulvinar on the basis that, as noted above, the ventral parts at least of human and macaque pulvinar show equivalent histochemical characteristics (Cola et al. 1999). Macaque dorsal pulvinar can also be subdivided histochemically, its subunits showing differential connectivity with parietal areas such as LIP and 7A (Gutierrez et al. 2000; Hardy and Lynch 1992). More importantly, however, the dorsal /ventral subdivision of the pulvinar as a whole earmarks two completely separate sets of cortical connectivities: the dorsal domain (including traditional PuM) communicates with parietal, superior temporal, frontal and cingulate cortices, whilst the ventral domain is associated with the occipito-temporal (or ‘ventral’) visual pathway (Baizer et al. 1993; Baleydier and Morel 1992; Shipp 2003).
The medial parietal eye field (mPEF - located within area 7m) is the most recently discovered, and least investigated (Raffi et al. 2007; Thier and Andersen 1998). A report of its subcortical connections [specifically case CB37, where the tracer deposit was centred on the reported anatomical locus of mPEF] emphasises structures in lateral thalamus, principally a continuous band of labelling extending rostrocaudally from VLp to dorsal pulvinar (Leichnetz 2001). Like PEF, but unlike FEF and SEF, this lateral thalamic territory heavily connected to mPEF includes the lateral posterior nucleus (LP) – one of the ‘top ten’ from Table S3. Lighter labelling was recorded in MDpc, Li and CL. Nuclei connected to FEF and SEF, but not mPEF include VA and Pf.

The full profile of thalamic activity listed in Table S3 is broader than the nuclei so far mentioned in the context of oculomotor circuitry. We accept that a number of the lower scoring nuclei could reflect the imprecision of the anatomical identification, as well as the inherent limitations of spatial resolution in the intrinsic BOLD signal. Indeed, several of these ‘fringe’ nuclei are neighbours of those discussed above. The focus of activity centred upon Pf, for instance, impinged upon several neighbours: the subparafascicular nucleus (sPF, 4.5) is sited where its name suggests, and the centre median nucleus (CM, 4.5) is directly lateral to Pf. The habenular nucleus (Hb, 0.5) is just caudomedial, and VPMpc (4.0) is a tiny nucleus lying directly anterior to Pf. PuA (3.0) and VPL (4.0) have several neighbours with still higher scores: PuA and VPL are sandwiched between PuM (6.0) and VLP (5.0), and they directly abut the posterior group nuclei - SG (6.0), Po (4.5) & VPI (2.5). Finally, MV (2.0), VM (4.0) and VLa (3.0) are all directly adjacent to the ventral anterior nucleus (VA, 4.0) – the latter being the lowest scoring nucleus of those known (in macaques) to be linked to FEF and 7A. It is possible that some of these fringe scores may represent unattributed activation of VA.

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