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Neural correlates of binocular rivalry in the human lateral geniculate nucleus

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When dissimilar images are presented to the two eyes, they compete for perceptual dominance so that only one image is visible at a time while the other one is suppressed. Neural correlates of such binocular rivalry have been found at multiple stages of visual processing, including striate and extrastriate visual cortex. However, little is known about the role of subcortical processing during binocular rivalry. Here we used fMRI to measure neural activity in the human LGN while subjects viewed contrast-modulated gratings presented dichoptically. Neural activity in the LGN correlated strongly with the subjects' reported percepts, such that activity increased when a high-contrast grating was perceived and decreased when a low-contrast grating was perceived. Our results provide evidence for a functional role of the LGN in binocular rivalry and suggest that the LGN, traditionally viewed as the gateway to the visual cortex, may be an early gatekeeper of visual awareness.

Binocular rivalry occurs when the input from the two eyes cannot be fused into a single, coherent percept. Rivalry can be induced experimentally by simultaneously presenting dissimilar stimuli to the two eyes, such as a vertical grating to one eye and a horizontal grating to the other. Rather than being perceived as a merged plaid, the two stimuli compete for perceptual dominance such that subjects perceive only one stimulus at a time while the other is suppressed from visual awareness[1]. Usually one stimulus predominates for several seconds, and the extent of competition between any pair of stimuli depends on stimulus properties, such as their relative contrast or spatial frequency[2,3]. Because the subjects' perceptual experiences change over time while the retinal stimulus remains constant, binocular rivalry provides an intriguing paradigm to study the neural basis of visual awareness[4].

The neural mechanisms underlying binocular rivalry have been much debated. In monkeys trained to report their perceptual experiences during rivalry, single-cell physiology experiments have demonstrated the existence of neural correlates of binocular rivalry mainly in higher-order visual areas[5]. The responses of about 90% of neurons in inferior temporal cortex increase when the neuron's preferred stimulus is perceived during rivalry, whereas only about 40% of neurons in areas V4 and MT, and even fewer in early visual areas V1 and V2, show such response enhancement[6,7]. On the basis of these findings, it has been concluded that binocular rivalry is mediated by competitive interactions between binocular neuronal populations representing the two stimuli at several stages of visual processing subsequent to the convergence of the input from the two eyes in V1 (the pattern-competition account). Alternatively, it has been suggested that binocular rivalry reflects competition between monocular channels either at the level of V1 or the lateral geniculate nucleus (LGN) and is mediated by mutual inhibition and reciprocal feedback suppressing the input from one eye[1,8]. This interocular-competition account has recently received support from fMRI studies showing that signal fluctuations in area V1 (ref. 9) and, more importantly, in the monocular V1 neurons representing the blind spot[10] are correlated with subjects' perceptual experiences. Neural activity of monocular V1 neurons varies according to subjects' perceptual reports, and the signal amplitudes measured during rivalry are similar to those measured during presentations of identical monocular stimuli; together, these observations suggest that rivalry is completely resolved in monocular V1 neurons. However, little is known about the role of subcortical processing stages—such as the LGN— in binocular rivalry.

The LGN is the thalamic station in the projection of the visual pathway from retina to V1 (ref. 11). It is typically organized into six layers, each of which receives input from either the contralateral or the ipsilateral eye and contains a retinotopic map of the contralateral hemifield registered to those of other layers. In addition to retinal afferents, the LGN receives input from multiple sources including V1 and the thalamic reticular nucleus (TRN). Given its anatomical organization and afferent projections, the LGN has often been considered a possible site of suppression in accounts of interocular competition[8,12]. However, single-cell recording studies in the LGN of awake monkeys viewing rivalrous stimuli have not found evidence to support this hypothesis[13].

We investigated the functional role of the human LGN in binocular rivalry using fMRI in subjects viewing dichoptically presented contrast-modulated grating stimuli[9]. We found that fMRI signals in the LGN and V1 were strongly correlated with subjects' perceptual experiences during binocular rivalry. The amplitude of fMRI signals increased when subjects perceived a high-contrast stimulus and decreased when they perceived a low-contrast stimulus. A similar response pattern—

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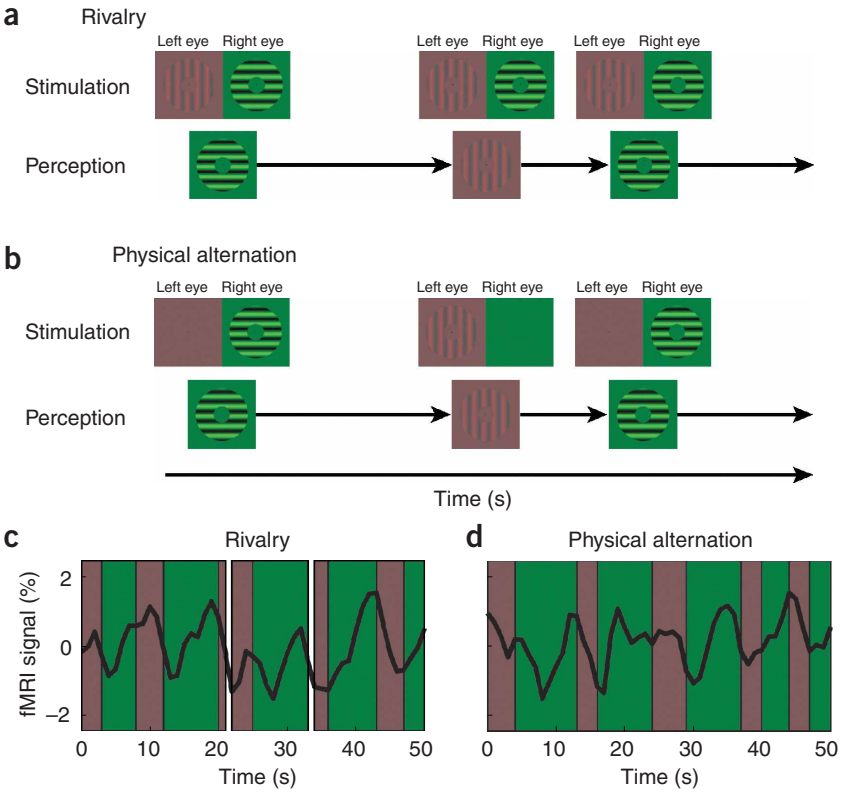

Figure 1 Experimental design and stimuli. (**a**) Subjects viewed red/green orthogonal sinusoidal gratings through matching filter glasses, with the higher-contrast horizontal grating visible to only one eye and the lower-contrast vertical grating to the other eye. Despite the invariant physical stimulation, subjects experienced binocular rivalry and reported switches in perception between horizontal and vertical gratings every few seconds. (**b**) The perceptual experience during rivalry was simulated in a physical stimulus alternation condition by presenting the green or the red grating to one eye and a uniform field to the other eye. The presentation times of alternating stimuli were identical to perceptual durations of the corresponding grating that the same subject reported during rivalry. All stimulus parameters were identical to the rivalry condition. In both experiments, subjects maintained fixation and indicated by button presses which grating was perceived. (**c**) Fluctuations of fMRI signals related to the perception of the high- and low-contrast gratings during binocular rivalry are evident in the raw time series of fMRI signals in the LGN from a single subject (S1). Phases during which the subject perceived high-contrast horizontal or low-contrast vertical gratings are shaded in green and red, respectively. Periods of intermittent piecemeal perception are not colored. (**d**) Raw time series of fMRI signals in the LGN from the same subject viewing physical stimulus alternations.

mimicking their perceptions during rivalry—was obtained when subjects viewed sequences of non-rivalrous physical alternations of the same stimuli. Our results provide the first evidence that, in humans, neural correlates of binocular rivalry can be found even earlier than V1 in the visual processing hierarchy: that is, in the LGN. These findings support interocular-competition accounts of binocular rivalry, including models of selective suppression of eye-specific LGN layers. Further, they indicate that neural correlates of conscious perception are not confined to cortical processing.

RESULTS

Five subjects participated in one scanning session for the rivalry experiment, followed by one session for the physical alternation experiment. In the rivalry experiment, subjects viewed superimposed sinusoidal gratings through red or green filter glasses such that one eye viewed a high-contrast, green, horizontal grating and the other viewed a low-contrast, red, vertical grating (**Fig. 1a**). The gratings filled an annular aperture centered on a fixation point and reversed contrast to minimize adaptation. The orthogonal orientations of the two gratings prevented them from being fused and also induced rivalrous perceptual oscillations between them. The luminance contrasts and reversal rates of the gratings were individually optimized for each subject so as to maximize the perceptual duration of the weaker, low-contrast stimulus (**Table 1**). Subjects maintained fixation and reported which grating was perceived by pressing a button; periods of mixed 'piecemeal' percepts of the two stimuli were indicated with a third button.

In the physical alternation experiment, we used sequential monocular presentations of the same grating stimuli to produce perceptions similar to, but physical stimulations different from, those in the rivalry experiment. This was achieved by presenting the low- or high-contrast grating to one eye and a uniform field to the other eye (**Fig. 1b**), using the identical temporal sequence of stimulus alternations reported by the same subject in the rivalry experiment. During these physical alternations, subjects maintained fixation and pressed buttons to indicate which grating they perceived.

In the LGN and V1, the amplitude of fMRI signals increases monotonically with stimulus contrast; reliable fMRI signals are typically evoked by stimuli of more than 10% contrast and signal saturation occurs with stimuli of more than 35% contrast[14–16]. Therefore, the different signal amplitudes evoked by low- and high-contrast stimuli can be used as a 'neural signature' of the LGN and V1 populations representing these stimuli—as was previously shown for physical and rivalrous alternations of contrast-modulated gratings represented in V1 (ref. 9). In the physical alternation experiment, we expected fMRI signals to increase when the high-contrast grating was shown monocularly and to decrease when the low-contrast grating was shown monocularly. Further, we reasoned that if the subjects' perceptual experiences during rivalry were reflected in the fMRI signals, signal fluctuations similar to those obtained during the physical alternations should reflect the reported percepts, despite the unchanging retinal stimulation. We used the contrast-modulated grating paradigm in both the rivalry and physical alternation conditions (i) to replicate previous findings showing that signal fluctuations in V1 were related to perceptual experience during rivalry[9,10], (ii) to investigate whether such signal fluctuations were present even earlier than V1 in the visual processing hierarchy—namely, in the LGN, (iii) to compare, within each area (that is, LGN and V1), the signal obtained during rivalry with that obtained during physical alternation, and (iv) to compare the signal obtained in one area, during rivalry or physical alternation, with its counterpart in the other area.

In each scanning session, we identified regions of interest in the thalamus and visual cortex by presenting flickering checkerboard stimuli alternately to the right and left visual hemifields, while the subject maintained fixation. The checkerboards activated the right and

Table 1 Stimulus conditions and perceptual dominance

		Contrast	Grating	High contrast			Low contrast		
Subject	Eye dominance	L/H (%)	Cyc/deg	*M*	%	Σ	*M*	%	Σ
S1	Left	17/70	0.4	9.3	68	116	4.0	29	112
S2	Right	17/70	0.4	4.2	55	201	3.0	39	201
S3	Right	14/70	0.5	6.1	31	77	4.9	35	108
S4	Right	20/70	0.4	5.1	49	306	3.5	34	309
S5	Right	20/70	0.4	4.0	59	346	2.0	28	332

The high-contrast grating was presented to the dominant eye. The contrast and spatial frequency of the gratings were adjusted individually to maximize the contrast difference while maintaining an adequate predominance duration. Psychophysical data for average perceptual duration (*M*), predominance—the percentage of time that the subject reported perceiving each of the two stimuli (%)—and number of occurrences (Σ) are reported for perceptions of high-contrast and low-contrast gratings. Predominance times do not total 100%; subjects perceived a piecemeal mixture of the stimuli during the remaining time.

left LGN and V1 (**Supplementary Fig. 1**). The locations of the functional LGN activations were consistent across subjects and across experiments and were in close correspondence to the anatomical locations of the LGN. The activated LGN volume, averaged over all subjects and all experiments, was 190 mm^3, similar to those observed in previous studies[15,17,18]. Activations in area V1 were identified based on anatomical or retinotopic mapping criteria.

Behavioral results

In the rivalry experiment, subjects experienced vigorous perceptual alternations between the horizontal high-contrast and vertical low-contrast gratings. For each subject, the perceptual durations of both stimuli varied randomly from 2 to 15 s and were distributed according to a gamma-shaped function (**Supplementary Fig. 2**), as is classically found in rivalry studies[2]. In accordance with such findings[2], the high-contrast grating—which is perceptually more salient—was perceived for significantly longer than the low-contrast grating, with some variability among subjects (**Table 1**). Across all subjects, the high-contrast stimulus was perceived for 5.1 ± 0.09 s (mean ± s.e.m.) compared to 3.1 ± 0.09 s for the low-contrast stimulus ($P \leq 0.001$; **Supplementary Fig. 2**). On average, subjects reported about 160 perceptual switches between the gratings; piecemeal perception occurred 3–34% of the time (**Table 1**).

fMRI results: binocular rivalry

fMRI signals in the LGN and V1 fluctuated while subjects perceived the rivalrous grating stimuli. The amplitude of the signals increased when subjects reported perceiving the high-contrast grating and decreased when they reported perceiving the low-contrast stimulus. These signal modulations can be seen in the raw time-series of the fMRI signals of single subjects. For example, shortly after subject S1 reported a perceptual switch from the low-contrast to the high-contrast grating, there was a sharp increase in the fMRI signal of the LGN (periods shaded in green, **Fig. 1c**). When the subject's perceptual experience changed to the low-contrast grating (shown shaded in red), the fMRI signals tended to decrease. Periods of piecemeal perception are not colored and were rare for this subject.

To analyze the fMRI time series obtained in the rivalry experiment in relation to subjects' behavioral responses, an event-related analysis was performed separately for the LGN and V1 of each subject. Mean fMRI signals were derived by averaging the fMRI time series across all events of a reported switch to the high-contrast grating and, separately, across all events of a reported switch to the low-contrast grating. The events were time-locked to the subjects' manual responses and spanned a period of 4 s before, and 9 s, after each response. These mean signals were then averaged across subjects and are presented as group data ($n = 5$) for the LGN and for V1 (**Fig. 2**). Although both gratings were constantly present during rivalry, the amplitude of the fMRI signals in

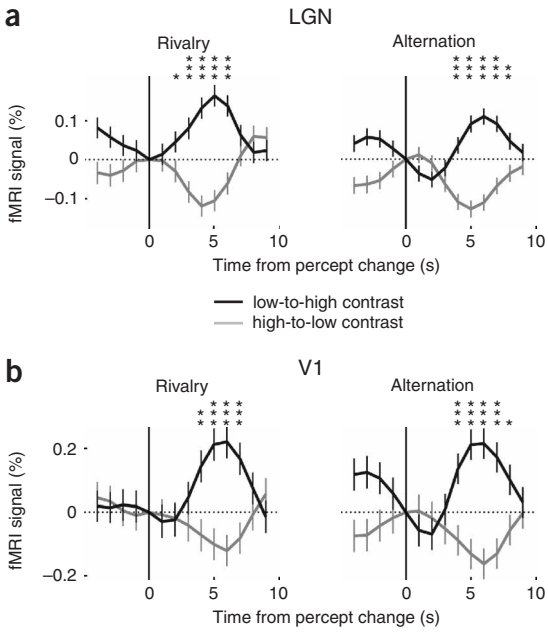

Figure 2 fMRI signals during binocular rivalry and physical stimulus alternations in the LGN and V1 (group analysis). (**a**,**b**) Data from (**a**) the LGN and (**b**) V1 of five subjects were combined across left and right hemispheres. Neural activity was averaged across all occurrences of perceptual switches from the low-contrast to the high-contrast grating (black curve) and across those from the high-contrast to the low-contrast grating (gray curve). The responses were time-locked to each subject's manual response, as indicated by the black vertical line at time point 0, and are shown within a relative time window of –4 to +9 s. All events were normalized, so that responses at time point 0 started at a value of 0% signal change. The vertical bar on each curve indicates one standard error of the mean. Asterisks indicate significant differences between data points of the two curves (one-tailed *t*-test, $*P < 0.05$; $**P < 0.01$; $***P < 0.001$). Left, results from rivalry scans. Right, results from physical stimulus alternation scans. Neural activity increased when subjects perceived the high-contrast stimulus and decreased when they perceived the low-contrast stimulus during rivalry conditions. A similar response pattern was found when subjects viewed physical alternations of the same gratings.

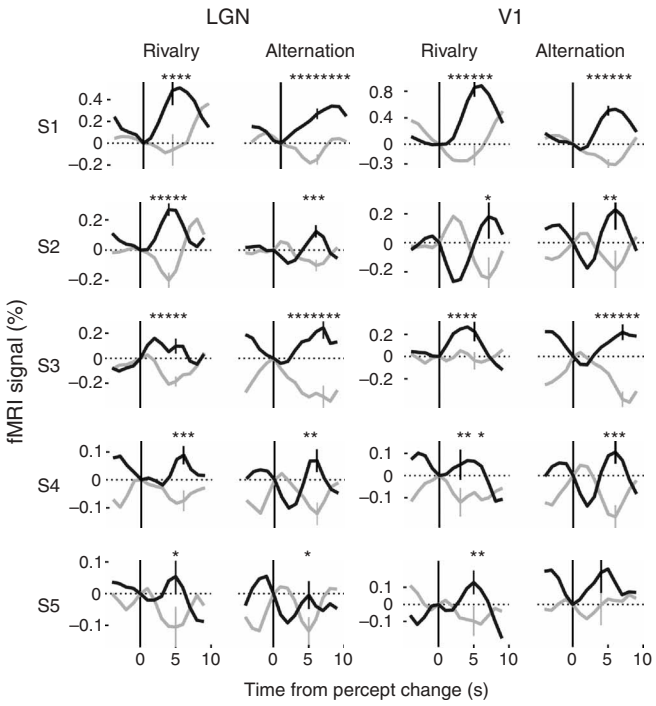

Figure 3 fMRI signals during binocular rivalry and physical stimulus alternations in the LGN and V1 (single subjects). Mean fMRI time series obtained while subjects (S1–S5) perceived the high-contrast grating (black) or low-contrast grating (gray) during binocular rivalry or physical stimulus alternations in the LGN and V1. For each subject, the fMRI signal increased in the LGN, and similarly in V1, after transitions to the high-contrast stimulus and decreased after transitions to the low-contrast stimulus. In the rivalry condition, differences between the high- and low-contrast fMRI time series were statistically significant for each individual subject, in both the LGN and V1, for at least the data point at the peak value of the curves. Each asterisk indicates a significant difference (one-tailed *t*-test; $*P < 0.05$) between a single point on the high-contrast time series and its counterpart on the low-contrast time series. Within subjects, the shape of the curves is markedly similar in the LGN and V1. Time series for physical alternations scans show a similar pattern as compared to those from the rivalry scans. Error bars, s.e.m. at the data point with the most significant response difference between the green and red curve in each panel. Other conventions are as in **Figure 2**.

both the LGN and V1 increased shortly after switches to the percept of the high-contrast grating (black lines) and decreased when the percept changed to the low-contrast grating (gray lines). The peak or trough of the hemodynamic signals occurred 3–6 s after the perceptual switches. Activity related to the percept of the high-contrast grating was significantly different from that related to the percept of the low-contrast grating for five data points in the LGN panel (**Fig. 2a**) and for four data points in the V1 panel (**Fig. 2b**; one-tailed *t*-test, $P \leq 0.05$ or below). Despite individual differences between subjects, the basic response patterns associated with the perceptual reports of high- and low-contrast gratings were present for each subject; moreover, for each subject, the two response patterns were significantly different from one another, at least at the point of peak response (one-tailed *t*-test, $P \leq 0.05$, **Fig. 3**).

The averaged fMRI activity associated with perceptual switches between high- and low-contrast stimuli showed a very similar pattern in the LGN and V1, as is apparent from both the group analysis (**Fig. 2**) and the single-subject analysis (**Fig. 3**). For individual subjects, there was a strong correlation between the amplitudes of the fMRI signal in the LGN and V1 ($r = 0.92$, $P \leq 0.03$, **Supplementary Fig. 3**). In agreement with previous studies[15,17,18], the amplitude of the signal was smaller in the LGN than in V1. Notably, the fluctuations in the V1 signal—reflecting the subject's perceptual experiences—in the rivalry condition confirm previous findings[9,10]. Our findings of similar fluctuations in the LGN signal extend these studies by demonstrating that the LGN is the first visual processing stage at which neural correlates of binocular rivalry can be observed.

To further examine the correlation between perception and the fMRI signal, we investigated whether the perceptual duration of each stimulus predominance period (which varied among subjects from 2 to 15 s) were reflected in the fMRI signals obtained on single trials. The perceptual events were sorted into four time categories (2–3 s, 3–5 s, 5–7 s and > 7s), and the fMRI signals were averaged separately for each category. The mean fMRI time series for the group of subjects was plotted as a function of the perceptual duration of the stimulus in the LGN (**Fig. 4a**). Because subjects rarely experienced the low-contrast stimulus for longer than 7 s, the fMRI signal for this time category is shown only for the high-contrast stimulus. It is evident that as the duration of the percept increased, the amplitude and dispersion of the fMRI signal increased. The averaged time series of the fMRI signal was fit to a Gaussian; in both the LGN and V1, the area under this curve was linearly correlated with perceptual duration ($r = 0.98$, $P < 0.0001$, **Fig. 4b**). This tight coupling between perceptual duration and the magnitude of the fMRI signal, in both the LGN and V1, suggests that both these structures form a neural circuit that is closely linked to visual awareness during binocular rivalry.

fMRI results: physical stimulus alternations

If the signal fluctuations measured during the binocular rivalry experiment do indeed reflect the responses of the neuronal population underlying the rivalrous perception of the high- and low-contrast stimuli, then mimicking these rivalrous perceptions by using physical alternations of the same stimuli should yield similar results. As expected from the contrast response functions of the LGN and V1

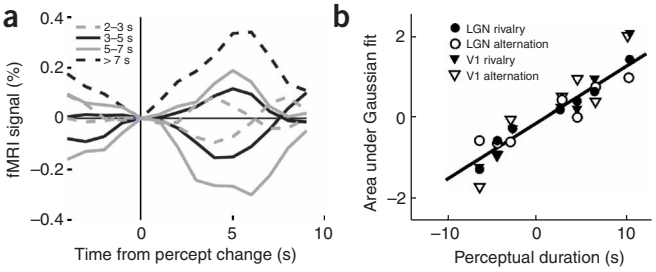

Figure 4 Effect of perceptual duration on fMRI signals. (**a**) fMRI time series averaged across subjects and time-locked to the subjects' manual responses are shown for the LGN as a function of perceptual duration. Dashed gray lines, 2–3 s; solid black lines, 3–5 s; solid gray lines, 5–7 s; dotted black line, >7 s (only shown for transitions to the high-contrast grating). The amplitude and duration of fMRI signals increased with increasing duration of the percept. (**b**) The time series data shown in **a** were fit to a Gaussian function. The area under these fitted curves was linearly correlated with the perceptual duration in the LGN ($r = 0.98$, $P \leq 0.02$). A similar correlation was observed with fMRI responses measured during stimulus alternations in the LGN and during both conditions in area V1. The abscissa of each dot corresponds to the average duration of trials in the corresponding perceptual duration category. Positive values indicate perceptual durations of the high-contrast grating; negative values indicate those of the low-contrast grating.

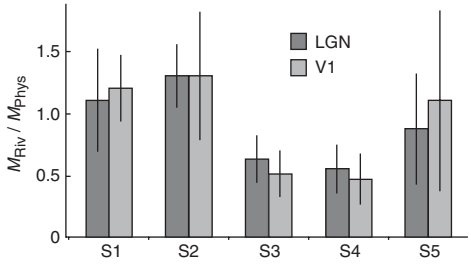

Figure 5 Comparison of fMRI signals during binocular rivalry and physical stimulus alternations in the LGN and V1. For each subject, the difference in signal amplitudes evoked by the high- and low-contrast gratings during rivalry or physical alternations was computed in both LGN and V1. The ratio of the signal differences obtained during rivalry to those obtained during physical alternations is plotted for each subject and area. The fractions of fMRI signals evoked during rivalry and physical alternations were similar in the LGN (dark bar) and in V1 (light bar). Vertical bars, s.e.m.

(refs. 14–16), fMRI signals increased when the high-contrast grating was presented and decreased when the low-contrast grating was shown. This pattern of response, markedly similar to that obtained during rivalry, was observed in the raw time-series (shown for the LGN in **Fig. 1d**), the group data (shown for the LGN in **Fig. 2a** and for V1 in **Fig. 2b**) and the single subject data (shown for the LGN and V1 in **Fig. 3**).

Previous studies have quantitatively compared the magnitude of the signal modulations obtained during rivalry with those obtained during physical stimulus alternations[9,10,19]. It has been reasoned that if the difference in signal amplitudes evoked by the two physical stimuli is similar to that evoked by the rivalrous stimuli, the invisible stimulus in the rivalry condition must be completely suppressed. We computed a 'suppression index' as follows: for each subject, we first determined the difference in signal amplitudes evoked by the high- and low-contrast stimuli, separately for the rivalrous condition and the physical alternation condition; we then calculated the ratio of the difference in the rivalry condition to that in the physical alternation condition (**Fig. 5**). An index value (that is, ratio) of 1 indicates equal differences in signal magnitude in the two conditions and can be interpreted as complete suppression of the invisible stimulus during rivalry. Index values between 0 and 1 indicate a smaller amplitude difference during rivalry than during physical alternation and may be interpreted as partial suppression. In the LGN, the level of suppression varied among our subjects as indicated by index values ranging from 0.5 to 1.3; for each subject we observed similar levels of suppression in the LGN and V1 (**Supplementary Table 1**). Three of the five subjects (S1, S2 and S5) had index values within one s.e.m. of 1, indicating a complete suppression of the competing input during rivalry at the level of the LGN and V1. The other two subjects (S3 and S4) had smaller index values, suggesting only partial suppression. Notably, subjects S1, S2 and S5 reported piecemeal perception rarely (for, respectively, only 3%, 6% and 13% of the time), whereas subjects S3 and S4 reported it more frequently (for 34% and 17% of the time, respectively). Less complete suppression might yield more frequent piecemeal perception, and it is possible that suboptimal viewing conditions and less stable percepts during rivalry contributed to the weaker signal amplitudes (and hence lower suppression indices) in these subjects. However, given the small number of subjects that were tested in this study, more evidence will be needed to support such an idea. Overall, the amount of piecemeal perception was loosely correlated with the suppression index ($r = -0.78$, $P = 0.11$).

DISCUSSION

By demonstrating systematic fluctuations in the fMRI signals associated with the subjects' perceptual experiences during binocular rivalry, we showed that, in humans, neural activity correlates with visual awareness as early as in the LGN. When superimposed orthogonal, contrast-modulated gratings were viewed dichoptically, fMRI signals in the LGN and V1 increased when subjects reported perceiving the high-contrast grating and decreased when subjects reported perceiving the low-contrast grating. The signal fluctuations observed during rivalry were similar to those evoked by physical alternations of the same monocular stimuli. Across subjects, the signal amplitudes evoked during rivalry were between 50% and 130% of those evoked by the physical alternations; further, the signal ratios were similar in the LGN and V1 for each subject. Because the input to the monocular LGN layers was unchanged during the perceptual oscillations during binocular rivalry, the modulation in LGN activity must be attributed to interactions within the nucleus or to modulatory inputs from other brain regions, such as feedback from V1. Notably, in both the LGN and V1, the magnitude and dispersion of fMRI signals evoked during rivalry were correlated with the duration of the subjects' perceptual experience, suggesting that neural activity at the earliest stages of visual processing reflects both the content and the duration of the percept and is therefore closely linked to visual awareness during binocular rivalry.

Previous neuroimaging studies of binocular rivalry have found correlations between the subjects' perceptual experiences and neural activity in V1 (refs. 9,20,21), including activity in the monocular representation of the blind spot[10]. Our results confirm these findings by demonstrating similar correlations between the fMRI signals in area V1 and subjects' perceptual states; further, we extend these findings by demonstrating that neural correlates related to perceptual experiences during binocular rivalry exist even earlier, at a subcortical processing stage—the LGN of the thalamus. Notably, the latter finding provides physiological evidence in support of accounts of interocular competition that assume inhibitory interactions between monocular channels before binocular convergence[1,8,12].

Advocates of these accounts have considered the LGN as a possible site at which the invisible stimulus is suppressed during binocular rivalry. Neurons in the LGN are exclusively monocular, with inputs from each eye segregated into separate layers. These adjacent laminae form an ideal substrate for inhibitory interactions between the two eyes; such an interaction would allow the signal from one eye to be selectively suppressed. Binocular interactions, predominantly inhibitory ones, have been widely reported in the LGN of both the monkey[22–24] and the cat LGN[25–30] and might provide a neural substrate for producing rivalry. These inhibitory interactions may be mediated by several anatomical pathways[11], including interneurons extending between LGN layers, corticogeniculate feedback from striate cortex (which comprises about 30% of the input to the LGN) and modulatory input from the TRN (which provides another 30% of the modulatory LGN input). One possibility is that feedback from the binocular neurons in layer 6 of V1 (refs. 31,32) to the monocular LGN layers could provide a descending control signal, indicating whether stimuli have been binocularly fused and regulating the strength of the inhibitory network[8]. The importance of feedback from V1 in controlling the observed LGN activity cannot be overemphasized. With the current temporal resolution of fMRI, it is not possible to determine whether the LGN controls V1 activity or merely inherits, through feedback, the binocular resolution (that is, the complete suppression of the input from one eye) that might take place in V1 or a higher cortical area. Another possibility is that the TRN (which receives inputs from V1, several extrastriate areas and the pulvinar), may serve as a node where

several cortical areas and thalamic nuclei of the visual system can interact so as to exert additional control on the LGN by modulating thalamocortical transmissions to LGN neurons via inhibitory connections[33]. It should be noted that these possibilities are not mutually exclusive. To summarize, therefore, on the basis of its anatomy and the organization of its retinal and cortical feedback input, the LGN seems to be in an ideal position to play an important functional role in binocular rivalry—as our present findings suggest.

The present and previous findings, that neural correlates of binocular rivalry exist at the earliest stages of visual processing[9,10,20,21], contradict results from single-cell physiology studies. In monkeys trained to report perceptual switches during binocular rivalry, the percentage of neurons whose firing rates correlate with the monkeys' perceptual experiences progressively increases across a hierarchy of cortical visual areas[5–7]. When their preferred stimulus is perceived during binocular rivalry, the vast majority of neurons in higher-order visual areas show increased activity; in contrast, only a small percentage of (almost exclusively binocular) neurons in early visual cortex do so. Most notably, although an early study reported the existence of a neural correlate of rivalry in the LGN of anesthetized cats[30], later studies with anesthetized cats[25] and awake monkeys[13] were unable to confirm that the LGN was indeed involved in binocular rivalry. The apparent discrepancies between single-cell recording and functional brain-imaging studies have been discussed elsewhere[9]—in terms of interspecies differences, eye movement confounds and differences between the blood oxygen level–dependent (BOLD) signal and single-unit activity—and will not be repeated here. In our view, it is possible that measures of neural activity at the population level (such as in fMRI), rather than at the single-cell level, may be better suited for uncovering large-scale modulatory activity. Small modulatory effects that cannot be reliably found by measuring neural activity at the single- or multi-unit level may be revealed when summed across large populations of neurons. Such a notion is supported by the finding that the BOLD signal correlates better with local field potentials, which reflect the synaptic input to an area, than with single- or multi-unit activity[34]. For example, modulatory inputs may have little effects on the spiking rate of single units but will still evoke strong responses in the BOLD signal. Thus, the discrepancies between previous electrophysiological and fMRI studies of binocular rivalry may be explained by sub-threshold modulations that are not reflected in the spiking output of neurons.

Owing to the spatial resolution limits of our fMRI technique, we were not able to image the individual layers of the LGN; however, comparing the fMRI signal in the LGN measured during rivalry with that measured during physical alternations of the same monocular stimuli may provide a measure of the degree of suppression among the layers. It has been reasoned that if binocular rivalry were fully resolved, one would predict similar magnitudes of signal fluctuation for perceived changes during rivalry as for physical stimulus changes: this would indicate that the input from the invisible stimulus was completely suppressed[9,10,19]. In the LGN, this would be instantiated as a suppression of activity in the eye-specific layers. Previous studies have reported that in V1, signal amplitude measured during rivalry is 50–85% of that measured during physical alternation[9], suggesting a partial suppression of the competing input; alternatively, in monocular V1 neurons, equal responses have been measured during rivalry and physical alternation[10], suggesting a complete suppression. Our results confirm both these findings: in three subjects, suppression was essentially complete, as evidenced by equal signal amplitudes during the rivalry and physical alternation conditions; by contrast, in the other two subjects, signal amplitudes were smaller during rivalry than during physical alternation, suggesting that only partial suppression occurred. Notably, both these last two subjects perceived a high proportion of piecemeal blends, which may indicate suboptimal viewing conditions and percepts that were, overall, less stable during rivalry. It is also possible that individual differences in response criteria contributed to this variability among subjects. Such factors may have led to weaker signals during the rivalry condition, as compared to the unambiguous physical alternation condition, and may account for the differences between individual subjects that were found here and in previous studies[9].

While interpreting our findings, we need to consider alternative possibilities for how signal fluctuations in the LGN and V1 might be related to subjects' perceptual experiences. As neural activity in the LGN is considerably modulated by visual attention[17], one possibility is that subjects paid more attention to the high- than to the low-contrast stimulus, and that the observed signal fluctuations were therefore caused by attentional switches. This interpretation is not satisfying, however, because the attentional demands of the task did not differ between the stimuli. If anything, the lower-contrast grating demanded more volitional attention because its predominance duration tended to be shorter. Switches to the high-contrast stimulus might initially capture attention, but the activity we observed was sustained over several seconds and was closely linked to the perceptual duration reported by the subjects. Another possibility is that the neural activity was confounded by systematic differences in eye movement patterns as subjects viewed the vertical or horizontal gratings. We were not able to measure eye movements in the MRI scanner because subjects wore filter glasses during the experiments and these obscured their eyes. However, our control experiment outside the scanner indicated that there were no differences in eye movement patterns for the two grating stimuli. Thus it seems unlikely that our findings could be sufficiently explained in terms of attentional modulation of neural activity or eye movement confounds.

Our study showed that neural activity that is closely linked to the duration and content of conscious perception is not confined to cortical processing as previously thought[35,36], but occurs even at the thalamic level. Much remains to be learned about the complex thalamic circuitry that subserves conscious perception in the LGN. From our study, we conclude that the LGN seems to be the first stage in visual information processing at which the neural correlates of visual awareness during binocular rivalry can be found. Our findings further suggest the need to revise the traditional view of the LGN as a mere gateway to the visual cortex. The LGN may, in fact, participate in a network of widely distributed cortical and subcortical brain systems, serving as an early gatekeeper of visual awareness.

METHODS

Subjects, visual stimuli and tasks. Five healthy subjects (3 male; 22–36 years old; normal or corrected-to-normal visual acuity) gave written informed consent for participation in the study, which was approved by the Institutional Review Panel of Princeton University. All subjects received training before the scanning sessions to ensure that subjects were able to report their perceptual experiences during binocular rivalry.

The rivalrous stimulus consisted of a pair of superimposed horizontal and vertical sinusoidal gratings (0.4–0.5 cpd) that were presented within an annulus (1.8–5.4°) centered at the fixation point. When these were viewed through a red filter glass by one eye and through a green filter glass by the other eye, only the horizontal grating was visible to the dominant eye and the vertical grating to the other eye (**Fig. 1a**). The two gratings also differed in color and luminance contrast. The vertical red grating was presented at 14–20% contrast and at a mean luminance of 0.5 cd m^{-2} when viewed through the matching filter. The horizontal green grating was presented at 70% contrast and at a mean

luminance of 0.6 cd m^{-2}. Each grating reversed contrast at a frequency of 1.1–1.4 Hz to prevent adaptation. Stimulus contrasts and reversal rates were individually adjusted for each subject so as to maximize the perceptual duration of the weaker stimulus (**Table 1**). Subjects were instructed to maintain fixation and to report their perceptual experience by pressing one of three buttons corresponding to the vertical red grating, the horizontal green grating or phases of an unstable piecemeal blend of the two.

The perceptual experience during rivalry was simulated in a physical stimulus alternation condition through the presentation of the green or the red grating to one eye, and a uniform field to the other eye (**Fig. 1b**). The presentation times of alternating stimuli were identical to the perceptual durations of the corresponding grating that the same subject reported during rivalry. To mimic the smooth transitions that were perceived during rivalry, stimuli were sinusoidally faded into each other over a 1-s period. Contrasts, colors and mean luminances were identical to those in the rivalry condition. As in the rivalry condition, subjects maintained fixation and indicated which grating was viewed by pressing buttons.

Neural representations of the peripheral annulus in the LGN and area V1 were localized by presenting a flickering checkerboard stimulus (contrast reversing at 8 Hz) in blocks of 16 s, alternating between the right and left hemifield (**Supplementary Fig. 1**)[17]. Subjects were instructed to maintain fixation during these presentations.

Data acquisition and analysis. Subjects participated in one or two scanning sessions for the rivalry experiment and an additional session for the physical alternation experiment. Data were acquired with a 3-T head scanner (Allegra, Siemens) using a standard head coil. Functional images were taken with a gradient echo, echoplanar sequence (TR = 1 s for rivalry and physical alternation scans, and 2 s for localizer scans; flip angle = 64° for rivalry and physical alternation scans, and 90° for localizer scans; TE = 30 ms; 64 × 64 matrix). Sixteen axial slices (3-mm thickness, in-plane resolution 3 × 3 mm^2) covering the thalamus and visual cortex were acquired in six series of 272 volumes each for the rivalry and physical alternation scans and six series of 128 volumes for the localizer scans. A high-resolution anatomical scan of the whole brain (MPRAGE sequence; TR = 2.5 s; TE = 4.3 ms; flip angle = 8°; 256 × 256 matrix; 1 mm^3 resolution) was acquired in the same session to align the functional images.

Data were analyzed using AFNI (http://afni.nimh.nih.gov/afni). The functional images were motion-corrected to the image acquired closest in time to the anatomical scan and normalized to percent signal change by dividing the time series by its mean intensity. Regions of interest (ROIs) in the LGN and V1 were defined based on activations obtained in the localizer scans. A square-wave function reflecting the contrast between left and right visual-hemifield stimulations was convolved with a gamma-variate function[37] to generate an idealized response function; this function was used as a regressor of interest in a multiple regression in the framework of the general linear model[38]. Additional regressors were included to account for variance that is due to baseline shifts between time series, linear drifts within time series and head motion. Statistical maps were thresholded at $P < 0.01$ and overlaid on anatomical scans. LGN activations were identified from contiguous voxels in the anatomical location of the LGN[15,17,18]. V1 activations were identified on the basis of their location in the calcarine sulcus and on retinotopic mapping using standard procedures in three subjects[18,39]. Data from the LGN and V1 were combined across hemispheres. Subjects who did not show bilateral LGN activation were excluded from the study.

Event-related fMRI time-series analyses were carried out on all activated voxels within a given ROI. Linear and quadratic signal trends were removed and the time series were low-pass filtered through a convolution with a three-point-width Hamming window. Mean time series of fMRI signals were calculated separately for switches from the high- to the low-contrast grating and vice versa, by averaging across all events during which subjects reported a perceptual switch within a restricted window of −4 s to +9 s relative to the manual response. All events were normalized, so that responses at time point zero started at a value of 0% signal change. Perceptual durations of less than 2 s were excluded from this analysis because they elicited fMRI signals too weak to be distinguished from noise. Differences in mean fMRI signals during switches from low to high contrast and from high to low contrast were tested for significance, with a two-sample, one-tailed *t*-test, at each of nine data points following the behavioral response. The subjects' perceptual experiences and the resulting fMRI activity were analyzed by grouping all single trials into one of four categories of perceptual duration (2–3 s; 3–5 s; 5–7 s; > 7 s). The mean fMRI signals were fit via nonlinear least-squares to a Gaussian, $f(t) = \alpha e^{-(t-\mu)^2/2\sigma^2}$, and parameterized as the area under the curve, $A = \alpha\sigma\sqrt{2\pi}$. A suppression index was defined by first determining the difference between the response amplitudes obtained for the two rivalrous stimuli and for the two physical alternation stimuli, and then calculating the ratio between the differences. An index value of 1 indicates fluctuations of equal magnitude during the rivalry and physical alternation conditions and could be interpreted as a complete suppression of the invisible stimulus during rivalry. Index values between 0 and 1 indicate that smaller amplitudes occur during rivalry than during physical alternations and could be interpreted as a partial suppression.

Eye movement control. Given that the two rivalrous stimuli were gratings perpendicular to each other, we considered the possibility that the two stimuli elicited different patterns of eye movements, thereby confounding the results obtained in the LGN and V1. Because the filter glasses obscured the subjects' eyes during scanning, it was not possible to monitor eye movements directly during these experiments. Instead, we carried out a behavioral control experiment outside the scanner by monitoring eye movements in all five subjects using an infrared eye-tracking device (ASL Model 5000 control unit and standard Model 504 remote optics, Applied Science Laboratories) while they viewed 20 alternating 8-s blocks of the vertical and horizontal grating stimuli without wearing filter glasses. We observed no significant differences in the mean or standard deviation of eye position, or mean eye velocity in either the vertical or horizontal direction (paired two-tailed *t*-test, $P > 0.05$), indicating that there were no obvious differences in fixation or eye movements when subjects viewed the two gratings.

Note: Supplementary information is available on the Nature Neuroscience website.

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COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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