A backward progression of attentional effects in the ventral stream

Elizabeth A. Buffalo[a,1], Pascal Fries[b,c], Rogier Landman[d], Hualou Liang[e], and Robert Desimone[d]

[a]Yerkes National Primate Research Center and Department of Neurology, Emory University School of Medicine, Atlanta, GA 30329; [b]Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, 6525 EN Nijmegen, The Netherlands; [c]Ernst Strungmann Institute in Cooporation with Max Planck Society, 60528 Frankfurt, Germany; [d]McGovern Institute for Brain Research, Massachusetts Institute of Technology, Cambridge, MA 02139; and [e]School of Biomedical Engineering, Drexel University, Philadelphia, PA, 19104

The visual processing of behaviorally relevant stimuli is enhanced through top-down attentional feedback. One possibility is that feedback targets early visual areas first and the attentional enhancement builds up at progressively later stages of the visual hierarchy. An alternative possibility is that the feedback targets the higher-order areas first and the attentional effects are communicated "backward" to early visual areas. Here, we compared the magnitude and latency of attentional enhancement of firing rates in V1, V2, and V4 in the same animals performing the same task. We found a reverse order of attentional effects, such that attentional enhancement was larger and earlier in V4 and smaller and later in V1, with intermediate results in V2. These results suggest that attentional mechanisms operate via feedback from higher-order areas to lower-order ones.

attention | Macaque | vision | feedback

Neurophysiologic and brain imaging studies in monkeys and humans have shown that attended stimuli evoke larger responses in visual cortex than unattended distracters (1–6), giving attended stimuli a competitive advantage for representation in the cortex (7). These top-down attentional effects are thought to be mediated in part by feedback from prefrontal and posterior parietal cortex (8–12) acting directly or indirectly on all visual areas in the dorsal and ventral stream, including V1. However, the mechanism of this feedback is unclear. In particular, a first-order question is whether the top-down feedback targets V1 [or even the lateral geniculate nucleus (LGN)] first and then is passed on successively to later areas, or whether it targets higher-order areas first and then is fed back to successively lower areas. Without an understanding of the basic functional anatomy of the attentional feedback, it will be difficult to make progress in unraveling the circuitry for attention.

The magnitude and timing of attentional effects on visual responses in all of the different visual structures should, in principle, give insight into the direction of attentional effects along the visual pathways. However, a comparison of the magnitude of attentional effects across visual areas in different studies leads to a confusing picture. On the one hand, imaging studies in humans typically find that attentional effects on evoked responses become larger as one moves from V1 into higher-order areas (13, 14). Several neurophysiologic studies in monkeys also often report small (4) or even nonexistent (6, 15, 16) attentional enhancement of firing rates to stimuli in the receptive fields (RFs) of V1 cells (17–19), compared with reliable findings of attentional effects in higher-order areas such as V4 in conventional target detection or discrimination paradigms. On the other hand, other primate studies report substantial attentional effects in V1 in complex tasks such as covertly tracking along curved lines with spatially directed attention (18). It has recently been demonstrated that even with a relatively simple selection task, very large attentional effects can be seen in V1 when entrainment to the rhythmicity of stimulus presentation helps optimize performance (20). Attentional effects in the LGN have also been reported in both monkeys (21, 22) and humans

(23), supporting the possibility that the attentional feedback may start at the very earliest stage of central visual processing and then is passed on to higher-order areas.

Similarly, the timing of attentional effects across areas leads to an uncertain conclusion. In the monkey LGN, McAlonan et al. (21) report extremely early but very transient enhancement of responses followed by a later, more sustained increase in response in a task with saccadic eye movements directed toward or away from a target in the RF. The transient effects occurred too quickly after stimulus onset to have been caused by cortical feedback impacting the LGN after the stimulus, but the later sustained attentional effects could have been. It is also not clear whether the very early transient attentional effects may have been specific to oculomotor tasks with saccades directed to the target (mediated, for example, by inputs from the colliculus) or would also be found in purely covert attentional tasks without saccades. By contrast, in a cross-modal attention task, Mehta et al. (24) failed to find effects in the LGN, and they found that attentional effects on responses in V1 were later than in V2 and V4, supporting the idea of a backward progression of attention effects. However, the visual stimulus in their study was a large diffuse light flash, and it is not clear whether the attentional effects were due to the up-down regulation of the entire visual cortex vs. auditory cortex, which could arise from feedback mechanisms that are very different from those involved in spatial attention to a target vs. distracter in the RF of a cell. Thus, the basic anatomic direction of attention effects in covert attention tasks remains unclear.

To determine the relative magnitude and order of attentional effects in the covert spatial attention paradigm along the visual pathway from V1 to V2 to V4, we therefore recorded from cells in all three areas in the same animals performing the same task (25–27).

Results

We recorded from 134, 93, and 116 neurons in V1, V2, and V4, respectively, in two rhesus monkeys performing a task of directed spatial attention. On each trial, two slowly drifting achromatic gratings were presented for several seconds in the parafoveal visual field, and on alternating blocks of trials, the monkey attended to the stimulus either inside or outside the recorded neuron's RF (Fig. 1F). Because of the blocked trial design, the monkey knew the location of the behaviorally relevant stimulus before it appeared, although we cannot say when the animal actually began to attend to that location. The monkey was rewarded for releasing a bar when it detected a subtle color change in the attended stimulus, while ignoring any change in the unattended stimulus. The color change could occur at any time

Fig. 1. Latency of attentional modulation of firing rate in areas V1, V2, and V4. (*A–C*) Red traces represent spike density plots of the average response in each area with attention directed INTO the neuron's RF (as illustrated by the "spotlight" of attention in the drawing in the top panel of *F*). Blue traces represent responses with attention directed OUT of the RF (*F*, *Bottom*). Responses are shown for area V1 (*A*), V2 (*B*), and V4 (*C*). Responses were aligned to the stimulus onset (0) and were smoothed with a Gaussian window of 30 ms. Shaded areas represent SEM. Vertical black lines represent the onset of the attentional modulation in each area. (*D*) Distributions of the latency of the attentional modulation are shown for each area. Red: V4; Blue: V2; Green: V1. Arrows denote median latencies for each visual area. (*E*) Cumulative distribution plot of the latency of attentional modulation in each area; colors represent the three areas as in the previous plot. (*F*) Cartoon depicting the stimuli in the blocked design task.

between 500 ms and 5,000 ms after stimulus onset, thus requiring the monkey to sustain attention for a long period. Neuronal responses were compared during trials when attention was directed to the stimulus located inside (attention IN) vs. outside (attention OUT) the RF. The sensory conditions were identical across attention conditions.

The percentages of cells showing sustained attentional effects on their firing rates in V4, V2, and V1 were 73% ($n = 85$), 44% ($n = 41$), and 26% ($n = 35$), respectively. To then estimate the earliest effects of attention in the population, we calculated the normalized average response histograms for all of these cells with attentional effects (positive or negative), which are shown in Fig. 1. The population latencies in V4, V2, and V1 were 170 ms, 440 ms, and 860 ms, respectively (see *Methods*). A bootstrap method was used to sample (n-1 latencies per sample) the latencies for each visual area 1,000 times, and the results were entered into a nonparametric ANOVA (Kruskal-Wallis), which revealed a significant main effect [$\chi^2(2) = 1,501.38$; $P < 0.0001$]. Post hoc tests (Tukey-Kramer) revealed significant differences for all pairwise combinations of areas (all P values < 0.05).

Computing the normalized response histograms based on all cells, regardless of whether they showed significant effects of attention, reduced the size of the attentional effects in the population and skewed some of the latencies to larger values (Fig. S1); however, the relative order of latencies was the same with all cells included. The average latencies of the attentional modulation across the population of all cells in areas V4, V2, and V1 were 220 ms, 460 ms, and 700 ms, respectively. This "reverse" pattern of the latency of attentional modulation across areas stands in contrast to the earliest visual evoked response onset latencies in the total cell population histogram, which were 65 ms, 40 ms, and 35 ms in V4, V2, and V1, respectively.

We then calculated the latency of attentional effects for each cell individually (see *Methods*). The distributions of individual latencies for all cells with significant attentional effects at any time are shown in Fig. 1*D*, and the cumulative distributions are shown in Fig. 1*E*. The median latencies in V4 ($n = 101$), V2 ($n = 37$), and V1 ($n = 24$) were 270 ms, 780 ms, and 1375 ms, respectively. A one-way nonparametric ANOVA revealed a significant main effect across areas [$\chi^2(2) = 38.64$; $P < 0.0001$], and post hoc analyses (Tukey-Kramer) revealed significant differences for all pairwise combinations except for the comparison between areas V1 and V2 (all significant P values < 0.05). Some cells in V4 (8% of total cells) showed significant effects of attention before the onset of the stimulus. This presumably occurred because in the blocked trial design the animals knew the location where the relevant stimulus would appear in advance.

To compare the magnitude of attentional effects across areas, we computed a contrast index of attentional effects from the period 1,000–3,000 ms after stimulus onset in the attention IN vs. attention OUT condition. As described above, this interval avoided the period just after stimulus onset when cells showed differences in attentional latencies. The attention index was computed according to the following formula: attention IN – attention OUT/attention IN + attention OUT for all cells. Fig. 2 shows the distribution of the index for all recorded cells across the three areas, which had a median value of 0.09 in V4, followed by 0.05 in V2 and 0.02 in V1 (sign test, all P values < 0.05). These indices correspond to an overall increase in firing rate with attention of 23%, 19%, and 5%, respectively, in the three areas. Thus, the magnitude of attentional effects across areas follows the same "backwards" trend as the distribution of latencies. A small number of cells in each area showed significant reductions
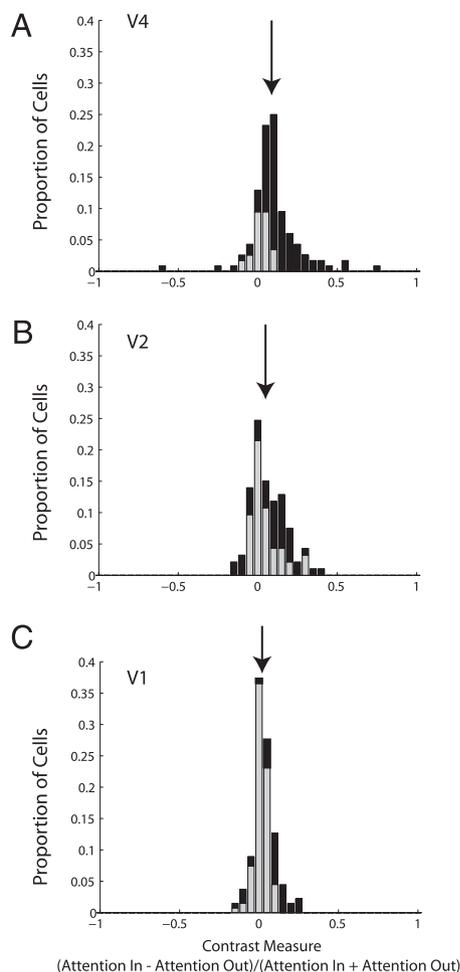
Fig. 2. Magnitude of attentional modulation. Distributions of the magnitude of the attentional effect (1,000–3,000 ms after stimulus onset) are shown for area V4 (*A*), V2 (*B*), and V1 (*C*). Black bars denote cells with significant attentional modulation.
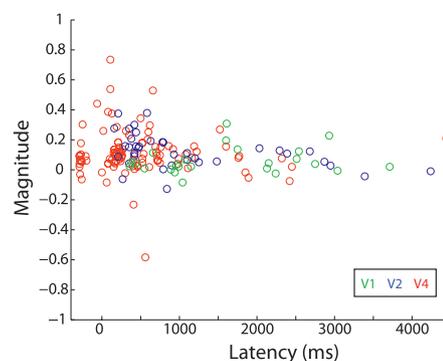

Fig. 3. Relationship between the magnitude of the attentional effect and the latency of the attention modulation. Scatter plot showing mean magnitude of the attentional effect (average contrast between attention IN and attention OUT from 1 to 2 s after stimulus onset) vs. the latency of attentional modulation for all neurons recorded from area V4 (red), area V2 (blue), and area V1 (green).

in response with attention to the RF stimulus (V1: 4% of total cells; V2: 13%; and V4: 7%).

We also examined whether there was a relationship between the magnitude and the latency of attentional effects. As shown in Fig. 3, across the population, there was no systematic relationship between the latency of attentional modulation and the magnitude of the attentional effect for individual cells (Pearson correlation, $r = -0.15$, $P > 0.05$). Additionally, there were no systematic differences in the monkeys' eye position across attention conditions that could have contributed to the attentional modulation (Fig. S2). We tested for transient attentional effects on just the "peak" of the initial sensory response to the stimulus in V1 and V2, similar to the analysis of McAlonan et al. (21) in the LGN and thalamic reticular nucleus (TRN), but, on average, there was no attentional enhancement of the initial peak response in either area.

Discussion

Is the enhanced processing of attended stimuli mediated by feedback that targets early visual areas first and is passed on to higher-order areas, or by feedback that targets higher-order areas first and is fed back to earlier areas with diminished effect and longer latency? Here, we found that neuronal responses were enhanced by spatially selective attention all along the ventral stream, but these effects were earlier and larger in V4 and pro-

gressively later and smaller in V2 and V1. The results in all three areas were obtained in the same monkeys performing the same task, which minimized the variance due to task and monkey variables. The results thus support the idea of a "backwards" progression of attentional feedback within the ventral stream.

We cannot say whether the backward progression of effects is actually mediated by direct feedback anatomic pathways from V4 to V2 to V1. In principle, all three areas could receive inputs from the same higher-level attentional structures, but with weaker and later feedback to V2 and V1. However, given the large proportion of cells showing attentional effects in V4, it seems likely that feedback from these cells would have a direct effect on visual responses in V2 and that cells showing an attentional effect in V2 would have an impact on V1. Cells in both superficial and deep layers of V4 and V2 project heavily back to the superficial and deep layers of V2 and V1, respectively (28–31). V4 itself receives direct feedback projections from frontal eye field and the posterior parietal cortex, both of which are implicated in attentional control (9–11), but this feedback projection is much weaker in V2 and may be nonexistent in V1 (32). If V1 (or the LGN) receives direct feedback from structures mediating attentional control, at high spatial specificity, it is not clear what would be the anatomic source of this feedback (see discussion of the LGN, below). Finally, it should be noted that lesions of V4 cause attentional impairments (33, 34), consistent with the idea that it plays a key role in mediating attentional feedback in the ventral stream.

The backward progression of attentional effects from V4 to V1 is consistent with the findings of Mehta et al. (24), who used a cross-modal attention design with a diffuse visual stimulus in monkeys, as well as the findings of Martinez et al. (35) based on the timing of attentional effects on event-related potentials in humans. Other monkey studies have found smaller attentional effects in V1 than in V4 (3, 4, 6), although the latencies of attentional effects were not reported in those studies. Human neuroimaging studies also typically find smaller attentional effects in V1 compared with higher-order areas.

The "normalization model of attention" (36) suggests that the effects of attention on a stimulus-evoked response can vary between a contrast gain and a response gain function, depending on the relationship between the size of the attended stimulus and the size of the receptive field. In the present study, the size of the stimulus was fixed but the relationship between the stimulus size and receptive field size varied among V1, V2, and V4, which may have influenced the attentional effects. However, with the high-contrast stimulus used in the present study, the model does not

predict the relative magnitudes of attentional effects that we found across areas, nor does it explain the longer attentional latencies in earlier visual areas found here. The backward anatomic progression of attentional effects seems a more likely explanation for the present results.

We are more confident of the relative order rather than absolute latencies of attentional effects that we found across the areas, because differences in the type of task, task difficulty, and stimulus variables will likely cause variations in absolute latencies. Local field potential (LFP) measures have been shown to have shorter absolute latencies (24). Future investigations of the relative sensitivity of single units vs. LFPs are needed to clarify this issue. However, a long latency of attentional effects in V1 could explain why some studies found little or no significant average enhancement of response with attention in V1, because these studies generally used short stimulus presentations (3, 6, 37, 38). Likewise, a long latency attentional effect in V1 provides an obvious explanation for why some imaging studies find robust effects of attention in V1 (13). The blood oxygen level–dependent signal in functional MRI averages activity changes over long intervals, which could easily include the late attentional effects observed in V1.

Recently, McAlonan et al. (21) found that attention serves to modulate visual signals at very short latencies in the LGN and the TRN. However, the short-latency attention effects found in the TRN and LGN were very transient, lasting no more than 100 ms. The LGN also showed more sustained attention effects at a longer latency of approximately 250 ms. The authors suggested that the short-latency, transient effects were mediated by top-down signals affecting TRN in advance of the target stimulus, because the monkey knew the location of the expected target in advance. Just as in the present study, attention was directed to the target location long before stimulus onset, which could have contributed to these very early effects in the TRN and LGN. They proposed that the transient inputs from TRN caused enhanced responses in the LGN (through a reduction of inhibition), and that these enhanced responses were then passed on to V1. However, because the attentional effects in TRN were so short lived, the longer latency attentional effects in the LGN must have resulted from a different mechanism. An obvious possibility is direct feedback from V1. If so, the long-latency attentional feedback from V1 to the LGN could be just another link in the backward cascade of attentional effects found in the present study. In the present study, we did not find any evidence for a very-short-latency, transient enhancement of responses with attention in either V1 or V2. We may have easily missed such transient effects if they were confined to small cells in layer 4C or other anatomic substructures in V1. However, a short-latency effect does not seem to be prevalent throughout the population of V1 cells, at least in the task used here.

Most studies of attention in monkey use tasks in which either an explicit cue or a blocked trial design informs the monkey of the behaviorally relevant stimulus or location in advance of its appearance. In such cases, it is not clear whether the feedback to visual cortex from high-level attentional systems begins before the stimulus appears or is triggered by the onset of the target stimulus. Whether cells show explicit attentional effects on ongoing activity before the target stimulus appears is variable across primate studies (4, 6, 39), suggesting that variations in task, stimulus, difficulty, or even individual monkey variables affect when the monkey begins to attend to the stimulus and therefore the attentional latencies and magnitude. In the present study, we found attentional effects in a few V4 cells just before the onset of the visual response in the blocked-trials task, suggesting that the feedback was initiated before the stimulus appeared. The modulation of activity before the stimulus appeared was small, however, and may have been insufficient to overly affect spontaneous activity in V2 or V1 at that early time.

What is the purpose of the attentional modulation of V1 and V2 cells if this modulation occurs later than in V4? One possibility is that this late attentional modulation in V1 and V2 is important in tasks for which very fine details are important. Coarse information at the attentional focus might be processed early in V4 and fine details later in V1 and V2 (40–42), which would also be consistent with longer behavioral latencies for difficult tasks requiring discrimination of fine details. If so, future studies might detect that attention affects the processing of fine details in V4 at long latencies.

Methods

Surgical Procedures. Experiments were performed in areas V1, V2, and V4 in four hemispheres of two male rhesus monkeys (*Macaca mulatta*), which followed the guidelines of the National Institutes of Health.

Two adult male rhesus monkeys were surgically implanted with a head post, a scleral eye coil, and recording chambers. Surgery was conducted under aseptic conditions with isofluorane anesthesia, and antibiotics and analgesics were administered postoperatively. Preoperative MRI was used to identify the stereotaxic coordinates of V1, V2, and V4. V4 recording chambers were placed over the prelunate gyrus. Additional plastic recording chambers were used for V1 and V2 recordings, centered 15 mm lateral and 15 mm dorsal to the occipital pole. The skull remained intact during the initial surgery, and small holes (≈3 mm in diameter) were later drilled within the recording chambers under ketamine anesthesia and xylazine analgesic to expose the dura for electrode penetrations.

Recording Techniques. In each recording session, four to eight tungsten microelectrodes (impedances of 1 to 2 MΩ) were advanced separately at a very slow rate (1.5 μm/s) to minimize deformation of the cortical surface by the electrode ("dimpling"). Recordings were performed in each of the three visual areas in separate recording sessions. Electrode tips were separated by 650 or 900 μm. Data amplification, filtering, and acquisition were done with a Multichannel Acquisition Processor (Plexon). The signal from each electrode was passed through a headstage with unit gain and an output impedance of 240 Ω. The signals were filtered with a passband of 100–8,000 Hz, further amplified, and digitized with 40 kHz. A threshold was set interactively, and spike waveforms were stored for a time window from 150 μs before to 700 μs after threshold crossing. The threshold clearly separated spikes from noise but was chosen to include multiunit activity. Off-line, we performed a principal component analysis of the waveforms and plotted the first against the second principal component. Those waveforms that corresponded to artifacts were excluded. Spikes were sorted into single units. When this was not possible, multiunits were accepted. The times of threshold crossing were kept and downsampled to 1 kHz. RF position and neuronal stimulus selectivity were as expected for the target part of each visual area.

Visual Stimulation and Experimental Paradigm. Stimuli were presented on a 17-inch cathode ray tube monitor 0.57 m from the monkey's eyes that had a resolution of 800 × 600 pixels and a screen refresh rate of 120 Hz non-interlaced. Stimulus generation and behavioral control were accomplished with the CORTEX software package (www.cortex.salk.edu). A trial began when the monkey touched a bar and directed its gaze within 0.7° of the fixation spot on the computer screen (Fig. 1F). After achieving fixation for 300 ms, the stimuli were presented. The stimuli consisted of two circular patches of drifting square-wave luminance grating (100% contrast, 2°–3° diameter, 1°–2°/s drift rate, 1–2 cycles per degree of spatial frequency). One stimulus was positioned inside the recorded neurons' RF, and the other was at an equal eccentricity in an adjacent visual field quadrant. The task of the monkey was to release the bar between 150 and 650 ms after a change in stimulus color (i.e., a change of the white stripes of the grating to photometrically isoluminant yellow). That change in stimulus color occurred at an unpredictable moment between 500 and 5,000 ms after stimulus onset. All times during this period were equally likely for the color change. Successful trial completion was rewarded with four drops of diluted apple juice. If the monkey released the bar too early or if it moved its gaze out of the fixation window, the trial was immediately aborted and followed by a timeout.

On the 50% of the trials in which the distracter changed before the target, the target nevertheless changed later on in the trial. Blocks consisted of 20 trials. The first two trials in a block were instruction trials in which only one of the two stimuli was shown and the monkey performed the task on that stimulus. The location of that stimulus was the target location for that block. For the remainder of the block, both stimuli were shown together without

any further cue. Thus, in the block design, the different attention conditions were physically identical. We recorded 100–300 correctly performed trials per attention condition.

Data Analysis. All data analyses were performed using custom programming in Matlab (The MathWorks). Sustained attentional affects for each cell were determined by averaging the firing rates across the period from 1,000 to 3,000 ms after stimulus onset for each trial. A t test was then used to compare these firing rates across attentional conditions. To calculate the latency of the attentional modulation on firing rate for both the population average and for individual cells, we compared firing rates (averaged over 10-ms nonoverlapping bins) for the two attentional conditions using a two-tailed t test. The first of three consecutive significant ($P < 0.05$) bins defined the onset of consistent attentional modulation.

1. Reynolds JH, Pasternak T, Desimone R (2000) Attention increases sensitivity of V4 neurons. *Neuron* 26:703–714.
2. Chelazzi L, Miller EK, Duncan J, Desimone R (1993) A neural basis for visual search in inferior temporal cortex. *Nature* 363:345–347.
3. Moran J, Desimone R (1985) Selective attention gates visual processing in the extrastriate cortex. *Science* 229:782–784.
4. McAdams CJ, Maunsell JH (1999) Effects of attention on orientation-tuning functions of single neurons in macaque cortical area V4. *J Neurosci* 19:431–441.
5. Kastner S, Pinsk MA, De Weerd P, Desimone R, Ungerleider LG (1999) Increased activity in human visual cortex during directed attention in the absence of visual stimulation. *Neuron* 22:751–761.
6. Luck SJ, Chelazzi L, Hillyard SA, Desimone R (1997) Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *J Neurophysiol* 77:24–42.
7. Desimone R, Duncan J (1995) Neural mechanisms of selective visual attention. *Annu Rev Neurosci* 18:193–222.
8. Moore T, Armstrong KM (2003) Selective gating of visual signals by microstimulation of frontal cortex. *Nature* 421:370–373.
9. Hopfinger JB, Buonocore MH, Mangun GR (2000) The neural mechanisms of top-down attentional control. *Nat Neurosci* 3:284–291.
10. Corbetta M, Shulman GL (2002) Control of goal-directed and stimulus-driven attention in the brain. *Nat Rev Neurosci* 3:201–215.
11. Kastner S, Ungerleider LG (2000) Mechanisms of visual attention in the human cortex. *Annu Rev Neurosci* 23:315–341.
12. Miller EK, Cohen JD (2001) An integrative theory of prefrontal cortex function. *Annu Rev Neurosci* 24:167–202.
13. Kastner S, De Weerd P, Desimone R, Ungerleider LG (1998) Mechanisms of directed attention in the human extrastriate cortex as revealed by functional MRI. *Science* 282:108–111.
14. Bles M, Schwarzbach J, De Weerd P, Goebel R, Jansma BM (2006) Receptive field size-dependent attention effects in simultaneously presented stimulus displays. *Neuroimage* 30:506–511.
15. Grunewald A, Bradley DC, Andersen RA (2002) Neural correlates of structure-from-motion perception in macaque V1 and MT. *J Neurosci* 22:6195–6207.
16. Marcus DS, Van Essen DC (2002) Scene segmentation and attention in primate cortical areas V1 and V2. *J Neurophysiol* 88:2648–2658.
17. Motter BC (1993) Focal attention produces spatially selective processing in visual cortical areas V1, V2, and V4 in the presence of competing stimuli. *J Neurophysiol* 70:909–919.
18. Roelfsema PR, Lamme VA, Spekreijse H (1998) Object-based attention in the primary visual cortex of the macaque monkey. *Nature* 395:376–381.
19. Ito M, Gilbert CD (1999) Attention modulates contextual influences in the primary visual cortex of alert monkeys. *Neuron* 22:593–604.
20. Lakatos P, Karmos G, Mehta AD, Ulbert I, Schroeder CE (2008) Entrainment of neuronal oscillations as a mechanism of attentional selection. *Science* 320:110–113.
21. McAlonan K, Cavanaugh J, Wurtz RH (2008) Guarding the gateway to cortex with attention in visual thalamus. *Nature* 456:391–394.
22. Vanduffel W, Tootell RB, Orban GA (2000) Attention-dependent suppression of metabolic activity in the early stages of the macaque visual system. *Cereb Cortex* 10:109–126.
23. O'Connor DH, Fukui MM, Pinsk MA, Kastner S (2002) Attention modulates responses in the human lateral geniculate nucleus. *Nat Neurosci* 5:1203–1209.
24. Mehta AD, Ulbert I, Schroeder CE (2000) Intermodal selective attention in monkeys. I: Distribution and timing of effects across visual areas. *Cereb Cortex* 10:343–358.
25. Fries P, Reynolds JH, Rorie AE, Desimone R (2001) Modulation of oscillatory neuronal synchronization by selective visual attention. *Science* 291:1560–1563.
26. Fries P, Womelsdorf T, Oostenveld R, Desimone R (2008) The effects of visual stimulation and selective visual attention on rhythmic neuronal synchronization in macaque area V4. *J Neurosci* 28:4823–4835.
27. Womelsdorf T, Fries P, Mitra PP, Desimone R (2006) Gamma-band synchronization in visual cortex predicts speed of change detection. *Nature* 439:733–736.
28. Salin PA, Bullier J (1995) Corticocortical connections in the visual system: Structure and function. *Physiol Rev* 75:107–154.
29. Henry GH, Salin PA, Bullier J (1991) Projections from areas 18 and 19 to cat striate cortex: Divergence and laminar specificity. *Eur J Neurosci* 3:186–200.
30. Rockland KS, Virga A (1989) Terminal arbors of individual "feedback" axons projecting from area V2 to V1 in the macaque monkey: A study using immunohistochemistry of anterogradely transported *Phaseolus vulgaris*-leucoagglutinin. *J Comp Neurol* 285:54–72.
31. Perkel DJ, Bullier J, Kennedy H (1986) Topography of the afferent connectivity of area 17 in the macaque monkey: A double-labelling study. *J Comp Neurol* 253:374–402.
32. Felleman DJ, Van Essen DC (1991) Distributed hierarchical processing in the primate cerebral cortex. *Cereb Cortex* 1:1–47.
33. De Weerd P, Peralta MR, Desimone R 3rd, Ungerleider LG (1999) Loss of attentional stimulus selection after extrastriate cortical lesions in macaques. *Nat Neurosci* 2:753–758.
34. Buffalo EA, Bertini G, Ungerleider LG, Desimone R (2005) Impaired filtering of distracter stimuli by TE neurons following V4 and TEO lesions in macaques. *Cereb Cortex* 15:141–151.
35. Martínez A, et al. (2001) Putting spatial attention on the map: Timing and localization of stimulus selection processes in striate and extrastriate visual areas. *Vision Res* 41:1437–1457.
36. Reynolds JH, Heeger DJ (2009) The normalization model of attention. *Neuron* 61:168–185.
37. McAdams CJ, Reid RC (2005) Attention modulates the responses of simple cells in monkey primary visual cortex. *J Neurosci* 25:11023–11033.
38. Yoshor D, Ghose GM, Bosking WH, Sun P, Maunsell JH (2007) Spatial attention does not strongly modulate neuronal responses in early human visual cortex. *J Neurosci* 27:13205–13209.
39. Reynolds JH, Chelazzi L, Desimone R (1999) Competitive mechanisms subserve attention in macaque areas V2 and V4. *J Neurosci* 19:1736–1753.
40. Ahissar M, Hochstein S (2000) The spread of attention and learning in feature search: Effects of target distribution and task difficulty. *Vision Res* 40:1349–1364.
41. Chen L (2005) The topological approach to perceptual organization. *Vis Cogn* 12:553–637.
42. Hochstein S, Ahissar M (2002) View from the top: Hierarchies and reverse hierarchies in the visual system. *Neuron* 36:791–804.

NEUROSCIENCE