Paying attention to natural scenes in area V1

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Natural scene responses in the primary visual cortex are modulated simultaneously by attention and by contextual signals about scene statistics stored across the connectivity of the visual processing hierarchy. We hypothesize that attentional and contextual top-down signals interact in V1, in a manner that primarily benefits the representation of natural visual stimuli, rich in high-order statistical structure. Recording from two macaques engaged in a spatial attention task, we show that attention enhances the decodability of stimulus identity from population responses evoked by natural scenes but, critically, not by synthetic stimuli in which higher-order statistical regularities were eliminated. Attentional enhancement of stimulus decodability from population responses occurs in low dimensional spaces, as revealed by principal component analysis, suggesting an alignment between the attentional and the natural stimulus variance. Moreover, natural scenes produce stimulus-specific oscillatory responses in V1, whose power undergoes a global shift from low to high frequencies with attention. We argue that attention and perception share top-down pathways, which mediate hierarchical interactions optimized for natural vision.

natural scenes | visual attention | primary visual cortex | neuronal populations | stimulus encoding

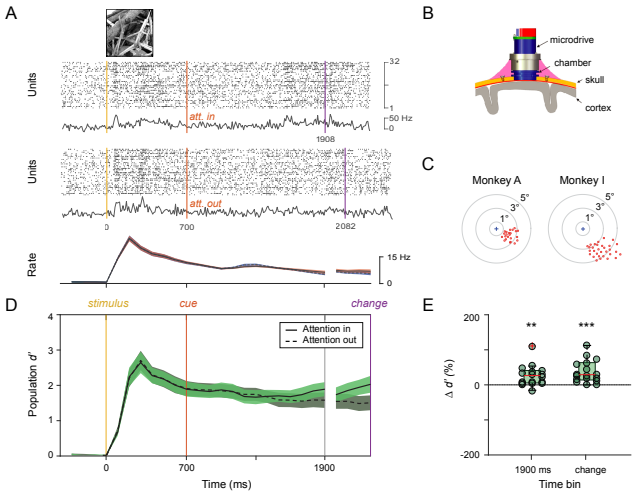

Fig. 1. Neuronal population recordings from primary visual cortex during an attention task with natural scene stimuli. (A) Multi-unit responses to the same stimulus in two example trials, corresponding to the attention in and attention out conditions. Markings represent timing of stimulus onset (yellow), attention cue (red) and stimulus change (purple). Bottom subplot shows grand average firing rates in the attention in and out conditions (legend as in D). (B) Chronic implantation device with movable electrodes (GrayMatter probe). (C) Receptive field locations in the two monkeys. (D) Effects of attention on stimulus discriminability along the trial, quantified by population d'. (E) Effects of attention on stimulus discriminability shown across sessions (reported in $\%$ change) for data aligned on stimulus onset (1700-1900 ms window) or stimulus change (200 ms window before change).

Introduction

Neuronal circuits across the visual hierarchy make efficient use of limited resources to encode complex natural scenes by exploiting their structural regularities (1, 2). Growing evidence suggests that during perceptual inference the visual system employs a hierarchical internal model of the visual environment that integrates current sensory evidence with previously acquired knowledge of natural scene statistics (3, 4).

When visual attention is directed towards a specific spatial location, it is thought to facilitate the perception of the targeted sensory input by prioritizing its processing. The signatures of this process can already be observed in primary visual cortex (V1). In this area, spatial and object centered attention modulate the firing rates of neurons responding to the selected stimuli (5–9). Responses in V1 are also shaped by context-dependent top-down signals that convey information stored in the hierarchically organized internal model of the world, required for the parsing of visual scenes (4). Thus, attentional mechanisms must interact with other sources of top-down influences raising the key question: how do these two processes — one that reflects the current allocation of attention and the other, the stored knowledge (priors) about statistical regularities of natural environments — cooperate in modulating responses in V1.

Here we performed parallel recordings of neuronal responses in the primary visual cortex of two macaque monkeys engaged in an attention task. We found that visual attention significantly improved the encoding of natural scenes across neuronal populations, both in the presence and absence of population firing rate changes. We hypothesized that these enhancements in natural scene encoding by attention took place through refinements of the responses to the common high-level features present in natural images, such as regularities in spatial structure, contrast and intensity distributions or texture properties. Given the hierarchical structure of the visual cortex, contextual information extracted and encoded at higher levels of the processing hierarchy, can inform and constrain the activity at lower levels of processing through feed-

back. In order to examine the possibility that attention acted primarily on mechanisms sensitive to these high-level features, we constructed synthetic stimuli that lacked the higher-level features characteristic of natural scenes. For these stimuli, the attentional benefits in stimulus encoding vanished, but could be recovered when the synthetic stimuli were modified to contain structured contours.

Results

We obtained parallel multisite recordings of multi-unit activity (MUA) (example trials in Figure 1A) and local field potentials (LFP) (32 channels, chronically implanted microdrive, Figure 1B) from area V1 of two awake behaving macaques (*Macaca mulatta*), while they performed a spatial attention task. Trials were initiated by a lever press while the monkey maintained fixation. After 500 ms two identical stimuli were presented at symmetrical locations on either side of the vertical meridian (distance from fixation spot 2.3-3.2° of visual angle), one of which covered the receptive fields (RFs) of the recorded units (example of RF centers in the two monkeys in Figure 1C). The fixation spot changed color, 700 ms after stimulus onset, cueing the monkey towards the "target" stimulus. Monkeys were rewarded if they responded to the rotation of the target stimulus. If they responded to the rotation of the non-cued stimulus, the distractor, reward was withheld and the trial was aborted. We performed analysis in 200 ms long sliding windows for the response interval from stimulus onset to 1900 ms (stimulus-aligned data), and for the 500 ms interval preceding the stimulus change (change-aligned data, time of change (TC)), thus excluding any activity evoked by the stimulus rotation or the motor response (further details in Materials and Methods).

Our initial goal was to examine the impact of attention on the stimulus specificity of the sustained population responses to natural scenes. Few electrophysiology studies have focused on the representation of natural stimuli in primary visual cortex (10–12), and how attention affects the decodability of natural scenes in V1 is still unclear. We quantified the stimulus-specificity of V1 neuronal population responses by measuring the differences in spiking patterns evoked by different stimuli compared to their variability across trials (population d', Materials and Methods). We found a significant increase in population d' with attention, i.e. responses evoked by different stimuli were more differentiable when the stimuli had been cued (attention-in) than when they had not (attention-out), particularly in the time windows preceding the stimulus change (Figure 1C and D, Wilcoxon signed-rank test; [1700-1900ms], P = 0.0012; [TC-200, TC], P = 0.00023; n = 18 sessions in 2 monkeys). Importantly, a significant difference in stimulus discriminability, was not only elicited by the cue, but also by intrinsic attention-related factors: when the trials from the *attention-in* condition were sorted based on the monkeys' reaction times (RTs), we found that trials with faster RTs had higher d' values compared to those with slower RTs, potentially indicating a graded improvement in stimulus decodability that was proportionate to the intensity of the attentional allocation (Figure S1, Wilcoxon signed-rank test; [1700-1900ms], P = 0.0043 ; [TC-200, TC], P = 0.0123; n = 18 sessions in 2 monkeys).

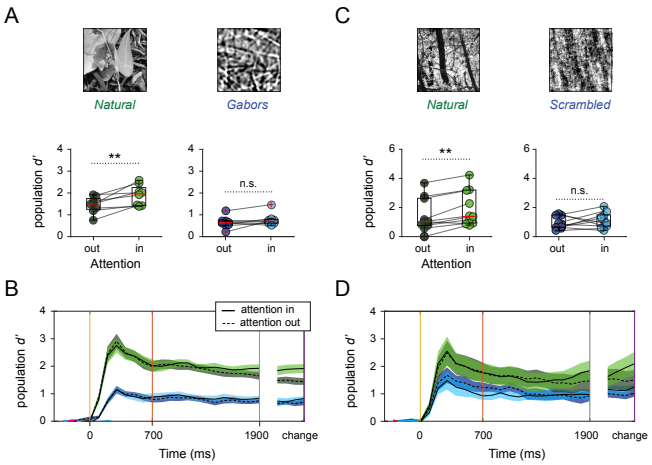

Fig. 2. Attentional modulation depends on stimulus content. (A) Stimulus discriminability d' for natural scenes (green) and synthetic images composed of independent Gabor filters (blue), shown across recording sessions (200 ms spike-count vectors before stimulus change) . (B) d' along the trial, 200 ms spike-count vectors, 100 ms sliding resolution, colors as in (A). (C) Stimulus discriminability d' for natural scenes (green) and phase-scrambled controls (blue), shown across recording sessions. (D) d' along the trial, colors as in (C).

In comparison, grand average firing rates only increased significantly with attention for the change-aligned and not the stimulus aligned data (Figure S1, Wilcoxon signed-rank test; [1700-1900ms], P = 0.1330 n.s.; [TC-200, TC], P = 0.0279; n = 18 sessions in 2 monkeys) and no significant increase was found in the comparison based on reaction times (Figure S1, P > 0.05). The attentional benefits in natural scene encoding were significant in individual animals and occurred both in the presence (monkey A), and absence (monkey I) of average firing rate changes. In monkey A, with receptive field locations closer to the fovea (Figure 1C left), attention increased the mean firing rate only before the stimulus change, in the interval corresponding to the enhanced stimulus encoding (Figure S2). In monkey I, with receptive field locations further from the fovea (Figure 1C right), attention *supressed* the mean firing rate ≈ 400 ms after the cue, and made no difference in the 1700-1900 ms window, in spite of a significant increase in stimulus encoding (Figure S2).

Contextual modulation of V1 responses conveys information about high-level inferences which can inform low-level inferences about the interpretation of local features (4). Given that the response properties of neurons at higher levels of the processing hierarchy capture the higher-order regularities of natural scenes, contextual modulation is likely more effective when such natural high-level features are present in stimuli. We hypothesized that if contextual modulation and attention share top-down pathways then the presence of high-level features constitutes a prerequisite for attentional enhancements in stimulus encoding across neuronal populations in V1.

To test this hypothesis we matched the natural scene stimuli, in every recording session, by an equal number of synthetic control images. The synthetic images were constructed in two ways: (1) by filter-scrambling and (2) by phase-

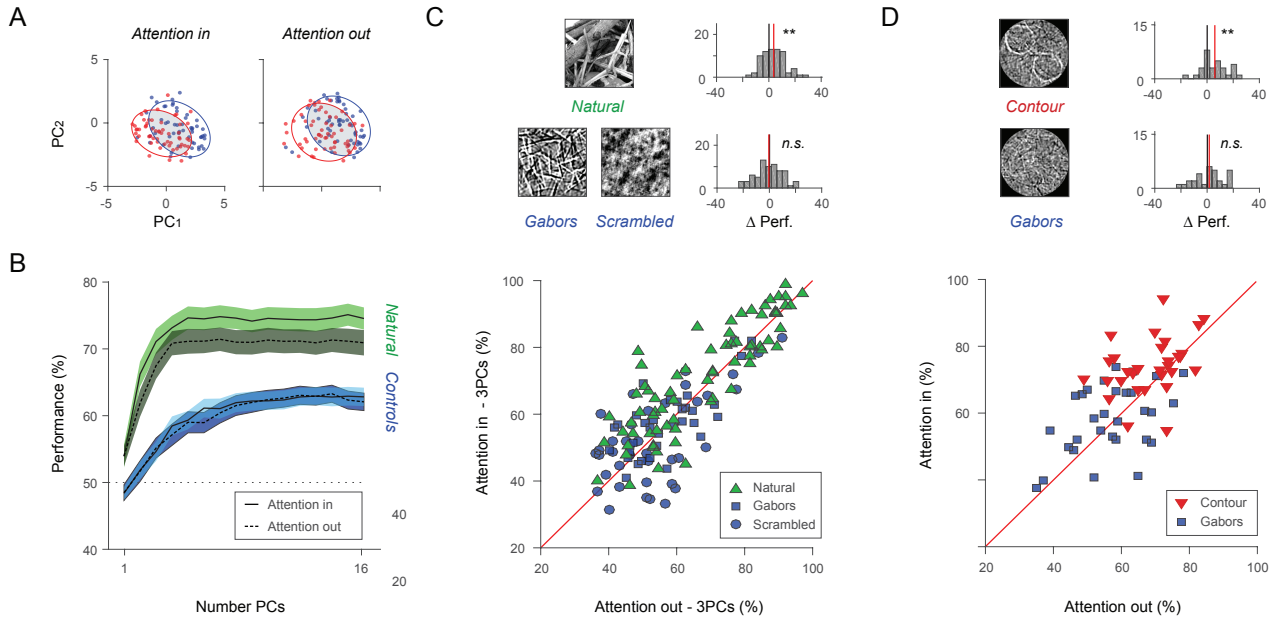

Fig. 3. Effects of attention on stimulus encoding in principal component space. (A) Example session depicting population responses to two natural scene stimuli (red and blue) for the two attentional conditions in the space described by the first 2 principal components (200 ms spike-count vectors, 1700-1900 ms from stimulus onset; each point represents a trial). (B) Stimulus decoding performance in principal component space for natural scenes (green) was higher than for synthetic stimuli (blue) and was modulated by attention (based on 1700-1900 ms spike count vectors; PCA was performed on pre-cue activity 500-700 ms window). Attentional differences in stimulus decoding are apparent from a low number of PCs, suggesting an alignment between attentional and stimulus variance. (C) Impact of attention on performance scores in low-dimensional projections (first 3 PCs) depends on stimulus type. Scatterplot shows performance scores for natural scenes (green) and synthetic controls (Gabors, blue squares; scrambled, blue circles; markers represent stimulus pairs n = 71; 18 recording sessions, 2 monkeys). Differences in performance with attention are significant for natural stimuli (top histogram, ** p-val < 0.01) but not controls (bottom histogram, n.s. p-val > 0.05). (D) Contour stimuli are compared to synthetic controls (n = 30 stimulus pairs from 5 recording sessions in 1 monkey). Differences in performance with attention are significant for contour stimuli not controls.

scrambling the original natural scenes (Figure 2A and B, more details in Materials and Methods). By construction, the synthetic controls contained no high-level features, but retained basic image properties: either the low-level structure preferred by V1 cells or the spectral content of the original natural scenes. We found that the response vectors evoked by both types of synthetic stimuli were less discriminable than those evoked by natural scenes and, in agreement with our hypothesis, the discriminability of neither type of synthetic stimuli was enhanced by attention (Figure 2, Wilcoxon signed-rank test; [TC-200, TC]; natural images P = 0.0078, Gabors P = 0.25 n.s.; n = 8 sessions in 2 monkeys; natural images P = 0.0039, scrambled P = 0.375 n.s.; n = 10 sessions in 2 monkeys). In contrast to the stimulus dependent differences of attentional effects on decodability, the effects of attention on grand average discharge rates were remarkably similar for natural and synthetic stimuli across units, suggesting a dissociation between the stimulus specificity of the population vector and the average firing rate (Figure S3).

These findings raise the question why responses to natural scenes profit more from attentional refinement than responses to manipulated stimuli or, in other words, what is special about natural scenes? Previous research has shown that natural images are statistically redundant, since light-intensities at neighboring locations are likely to be correlated and consequently, they can be efficiently compressed (13, 14). Structured compressible visual stimuli are well captured by neuronal population dynamics in low-dimensional manifolds (12, 15–17), but see (18). How could such low-dimensional collective representations of natural images in V1 be further optimized by the allocation of top-down attention? Are the top-down attentional signals largely matching the bottom-up evoked responses to natural stimuli?

Given that, in the current task, the stimuli precede the attentional cue, we could directly enquire whether the variance added by attention was orthogonal to, or belonged to the same dimensions as the variance produced by the stimulus. Specifically, in each recording session, we projected the activity from the time window preceding the stimulus change (1700-1900 ms) into the principal component space defined by activity recorded after the stimulus onset but before the presentation of the attentional cue (500-700 ms). We reasoned that if the attentional variance was largely aligned to the stimulus variance, the attentional differences in stimulus decodability would become apparent in the low-dimensional space described by the first components. This is indeed what we found (examples in Figures 3A and S4).

We quantified the attentional differences on natural-scene representations in principal component space by applying a decoding technique. Specifically, a cross-validated Bayesian decoder was trained to predict stimulus identity based on data projections (spike-count vectors over the 1700-1900 ms interval) into the pre-cue PCA space described by the first k principal components, and test performance was estimated in this same space based on unseen trials (Figure 3B, 5-fold validation, details in Materials and Methods). We found

that natural scenes could be well distinguished in principal component space (Figure 3B, decoding performance range $61.8 - 75.13\%$ for k >=2) and importantly, the attentional benefits in stimulus encoding were apparent already for a small numbers of components (Figure 3B, Wilcoxon signed-rank test; P < 0.015 for k >=2; Holm-Bonferroni correction showed significance for all k >=2; n = 71 stimulus pairs, 18 sessions, 2 monkeys); scatterplot and histogram of attentional effects for k = 3 are shown in Figure 3C and D). In comparison, the synthetic images performed more poorly (Figure 3B, decoding performance range $51.7 - 63.3\%$ for k >=2) and showed no attentional modulation (Figure 3B, Wilcoxon signed-rank test P > 0.05 for all k; n = 71 stimulus pairs, 18 sessions, 2 monkeys), in spite of residing in principal component spaces with similar levels of overall variance (Figure S5C).

By comparing V1 neuronal responses to natural scenes and synthetic low-level images we found that the effects that attention has on the stimulus specificity of the population vector are influenced to a large extent by the stimulus content. To distill these findings to the essential ingredients, we generated an additional set of synthetic stimuli that combined Gabor functions into simple contour-like patterns, thus introducing the kind of higher-level structure expected to elicit differential responses at higher processing stages. In these additional datasets, both main effects described previously were reproduced: the structured contour stimuli were well distinguished in principal component space, while the unstructured controls were not (decoding performance range contour stimuli $66.4 - 74.7\%$ and synthetic Gabors $54.9 - 60.4\%$ for k >=2, Figure S5) and the attentional effects were specific to the contour stimuli and captured already by a low number of components (contour stimuli Wilcoxon signed-rank test; P < 0.05 for all k >=2; n = 30 stimulus pairs, in 1 monkey; control images P>0.05 for all k, Figure S5; scatterplot and histogram of attentional effects for k = 3 Figure 3C). Interestingly, trial-shuffling within stimulus condition reduced the attentional differences in decoding performance for the contour stimuli and the original natural scenes, suggesting that even in these low-dimensional projections decoders benefitted from the intact correlation structure present in the data (Figure S5). Overall, by constructing synthetic images with controlled statistical structure, we confirmed that the attentional benefits in stimulus encoding across collective neuronal responses in V1 were specific to images containing higher level structural regularities. Such images are more likely to engage structured feedback from higher-levels of processing.

Finally, we investigated the impact of attention on the oscillatory network dynamics of V1 responses to natural stimuli. Average LFP power spectra across all recording sessions with natural scenes, when attention was directed towards the stimulus, are shown in Figure 4A. Across trials, reaction times in the attention-in condition were positively correlated with the LFP power in the theta and beta bands and negatively correlated with the LFP power in the gamma band (Spearman correlation; theta $r = 0.18$, $p = 1e-11$; beta $r = 0.08$, $p = 0.002$; gamma $r = -0.12$, $p = 1e-05$). These correlations were also significant for the synthetic stimuli, thus presumably reflecting task-related effects (Spearman correlation; theta $r = 0.11$, $p = 3e-5$; beta $r = 0.07$, $p = 0.008$; gamma $r = -0.11$, $p = 3e-04$). When trials were separated based on cue information, we found that attention strongly reduced the low-frequency oscillations below 40Hz and weakly amplified the high-frequency oscillations above 60Hz (Figure 4B). Along the trial, these attentional differences in LFP power started ≈ 300ms after the attentional cue and increased gradually with the expectancy of the stimulus change (Figure 4C, individual monkeys in S6).

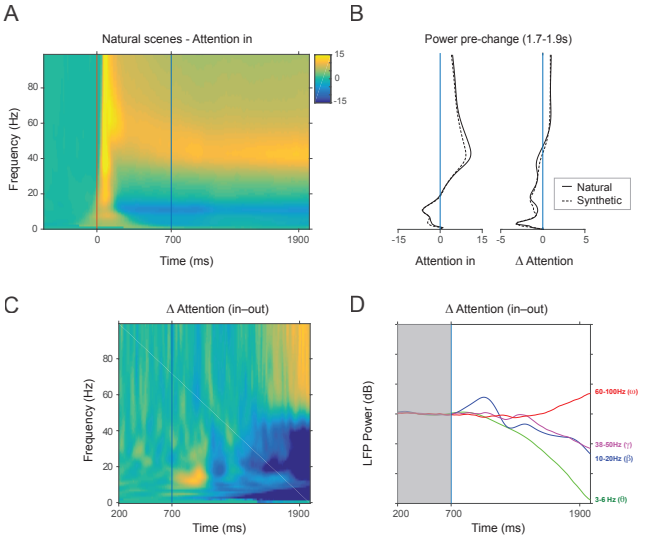

Fig. 4. Dynamics of LFP power spectra during the attention task with natural scenes. (A) Within-trial time-frequency representations of log-transformed LFP power to natural scenes in the attention-in condition (pre-stimulus baseline substracted, 18 sessions, 2 monkeys). Stimulus onset (0ms) and cue onset (700ms) are marked by vertical lines. (B) LFP power and its attentional modulation for the window preceding the stimulus change (1700-1900 ms). Natural scenes (continuous) and synthetic stimuli (dotted) show similar attentional modulation, suggesting that mostly task-related effects were captured by the LFPs. (C) Time-frequency differences in LFP power with attention for natural stimuli exhibit a gradual shift in power from lower to higher frequencies ≈ 300ms after the attentional cue (marked by vertical line at 700ms). (D) Attention decreases the power of theta (3-6Hz, green) and beta oscillations (10-20Hz, blue) and modestly increases the power of high-frequency oscillations (60-100Hz, red).

Previous studies have implicated gamma oscillations in the representation of natural images (12, 19). Here, we found, in both animals, that the LFP power in the gamma band was higher for the natural scenes compared to the low-level synthetic images (Figure S6), consistent with previous suggestions that visual stimuli with higher structural predictability result in stronger gamma oscillations (12). Nonetheless, attentional modulation of LFP power in the gamma band showed a reduction in monkey A and a slight increase in monkey I, and was therefore difficult to interpret (Figure S6). Interestingly, the identity of natural scenes could also be well decoded from the vector of the simultaneously recorded LFP signals, if frequencies >40Hz were used for analysis (Figure S7). However, no attentional improvements in stimulus decodability were detectable from LFPs, except at the highest frequencies in one monkey (monkey I, >88Hz, Figure S7).

Discussion

In this study, we found that attention improves the representation of natural scenes across neuronal population vectors in area V1. By constructing synthetic stimuli with controlled statistical structure, we could link the attentional benefits in stimulus encoding to the presence of higher-order regularities that are known to be abundant in natural images.

In our experiments, animals were trained to respond swiftly to the rotation of the cued stimulus, not to recognize particular features in the image. Thus our task was a classical spatial attention task. In agreement with previous studies allocating spatial attention caused moderate increases in discharge rate, reduced power of low frequency oscillations and enhanced power in the high frequency bands of local field potentials. As expected, these effects did not depend on stimulus structure. In agreement with psychophysical and previous electrophysiological investigations this indicates that spatial attention enhances the salience of responses (20). However, allocating spatial attention had the additional effect of enhancing selectively the decodability of population responses of V1 to the attended stimulus, provided that the stimulus contained higher order statistical regularities characteristic of natural scenes. These effects on decodability could not be attributed to a global increase of excitability because they occurred also in the absence of rate changes. Evidence indicates that the structural features characteristic of natural scenes are processed only at higher levels of the visual processing hierarchy (21, 22). This implies that allocation of spatial attention must have interfered with feature sensitive top-down mechanisms, raising the question how these two processes interact.

Visual scenes are evaluated by comparing sensory evidence with previously acquired priors about the statistical structure of natural environments (1). These internal priors are stored in the functional architecture of cortical circuits at all levels of the visual processing hierarchy and some of these circuits get refined by experience to capture characteristic properties of the visual environment (2, 3, 23). Recombination of feedforward connections renders neurons selective for increasingly complex constellations of features (22, 24, 25), and the abundant horizontal intra-areal and feed-back connections between processing levels allow for contextual modulation of these feature selective responses (26, 27). These modulations impact stimulus saliency (28) and perceived brightness (29, 30), support perceptual grouping (31), and figure-ground segregation (32–35). The electrophysiological correlates of these interactions consist of changes in discharge rate and/or synchrony and these effects tend to have longer latencies than the initial phasic responses. Therefore it has been concluded that the context sensitive processes are mediated by recurrent interactions within cortical areas and top down signaling across processing stages. In the following we discuss how allocation of spatial attention that is also supposed to be mediated by top-down connections interacts with these feature sensitive mechanisms.

Attentional influences on visual processing have traditionally been divided into spatial (36–38) and object/feature-based attention (39, 40) and it has been proposed that both contribute in complementary ways to the parsing of image content (41, 42). Our results support this notion and provide some indications as to the mechanisms underlying these complex interactions, in the context of natural stimulation. In the present task, the allocation of spatial attention contributed additional variance in the first principal components of responses to natural but not to manipulated images and thereby enhanced decodability of the former. The finding that spatial attention had no effect on decodability of manipulated stimuli indicates that spatial attention has per se no refining effect on distributed stimulus representations in V1, but selectively improves representations of stimuli characterized by the higher order regularities of natural scenes. Abundant evidence indicates (21) that these higher order regularities are evaluated by downstream areas of the visual processing hierarchy. Therefore, the enhanced decodabilty of responses to natural images is likely to have been mediated by top-down signals from these areas. This raises the question, why these high-level processes were more involved when spatial attention was allocated to the stimulus. One possibility is that higher level processes do not engage by default even when stimuli match high-order priors but get involved only for stimuli to which spatial attention is allocated. In this case spatial attention would be a prerequisite for the engagement of mechanisms that provide top-down signals commonly attributed to feature or object specific attention, suggesting some hierarchy in the interactions between spatial and object centered or feature specific attention. An alternative possibility is that higher level processes engage by default when stimuli match high-order priors and work cooperatively alongside spatial attention. In this case, the visual system performs a search that attempts to infer task-relevant features of an image based on both the spatial aspects of the visual scene and the low-level and high-level structural regularities. Thus spatial and object-based attention act in unison and share an internal representation of features, with the inference slowly unfolding over reciprocal interactions across multiple hierarchical levels of processing.

The latter interpretation is supported by the observation that the natural scenes could be discriminated surprisingly well, given the relatively low number of units and their location in area V1 (Figures 2 and 3), regardless of the attentional cue. The fact that the discriminability of natural stimuli was high also when attention was directed away from the stimulus implies that the natural scenes were efficiently encoded, irrespective of the attentional state. Previous studies found that an efficient encoding of global scene statistics remained possible in situations associated with reduced visual attention (43). In such cases, the visual cortex is thought to extract a compressed "summary" code that does not capture the full distribution of local details, yet provides a good representation of group features. Since natural scenes are structured, redundant, low-dimensional images, they are compressible. In comparison, the low-level synthetic images are difficult to compress and must be represented exhaustively, without the help of internally generated or previously acquired priors on summary statistics. Thus the resulting neuronal activ-

ity vectors to synthetic stimuli are likely to inhabit higher-dimensional or more variable substates, potentially accounting for the overall poorer performance of the classifier.

A cross-validated principal component analysis captured the efficient encoding of natural scenes across neuronal populations in V1. In principal component space, the response vectors to natural stimuli reflected their low-dimensionality and could be well described by few principal components. The higher-order stimulus structure, characteristic of natural scenes, was thus well-separated by low-dimensional subspaces. In a sense, these subspaces reflect some of the higher-order selectivity normally associated with responses of individual neurons at higher levels of processing (44, 45). The finding that spatial attention enhanced the encoding of natural scenes along the dominant representational dimensions, suggests refined, cooperative interactions across multiple levels of the visual hierarchy. The match between representational and attentional signals in V1 shows a remarkable alignment, likely advantageous for efficient processing. This match appears compatible with previous results highlighting similarities between the effects of representational learning and attention in downstream area V4 (46).

In agreement with previous studies, spatial attention modulated the dynamics of responses as reflected by changes in the frequency distribution of LFP power. After the arrival of the attentional cue, the responses to the attended stimulus showed a strong reduction in spectral power for lower frequencies and a modest enhancement for higher frequencies, for both natural and manipulated stimuli. This shift in LFP power from low to high frequencies built up gradually from the onset of the cue to the temporal window preceding the stimulus change (Figures 4 and S6). This kinetics resembled a hazard function reflecting the increasing probability of having to execute a response, suggesting that the reduced power of the low frequency oscillations is probably related to the increased readiness to act. In agreement with this interpretation the oscillatory power in the theta and beta bands of responses to the target stimulus was positively correlated with reaction times in the attention-in condition. These results are consistent with previous reports. Beta oscillations have been shown to decrease during the preparation of a motor response (47) and theta band power has been shown to decrease with attention (48).

In addition to these attention dependent effects on dynamics, we observed an interesting build up of gamma oscillations for natural, but not for synthetic stimuli, over the course of the trial (Figure S6). Gamma oscillations are thought to result from a feedback loop between pyramidal cells and fast-spiking interneurons (49, 50) . Recent evidence indicates that the associated synchronization of discharges acts as an internal resonance filter of stimulus content (12, 51). Synchronisation of discharges in the gamma frequency range increases for responses to features that are well predicted by the embedding context. This is the case for regular gratings, but also for homogeneous colour stimuli (52) and redundant, compressible natural scenes (12). Our present findings are in line with this evidence. Natural scenes induced more gamma oscillations than the synthetic stimuli, likely because they contain more compressible features and better match the priors resident in the synaptic weight distribution of cortical networks. In our study the strength of gamma band oscillations was negatively correlated with reaction times in trials corresponding to the attention-in condition. This agrees with previous findings from area V4 (53) and also with our observation that the gradual shift in power from low to high frequency oscillations is related to the readiness to act (see above). In agreement with previous studies is also the finding that attention enhances the power of the broad band high frequency activity that likely reflects increases spiking and synaptic activity (54). However, previous studies on the attentional modulation of gamma oscillations in V1 have reported mixed results (55) and this heterogeneity is reflected also by our results. The attentional cue caused an increase in gamma power in one animal and a decrease in the other. We speculate that the manner in which top-down attentional signals engage the local excitatory-inhibitory subnetworks in V1 may differ as a function of the neurons' receptive fields sizes and locations, which in this work was not explored.

One puzzling aspect of our findings is the confinement of the attentional benefits on stimulus encoding to the temporal interval preceding a change in the cued stimulus. Since the task requires only a suppression of reflexive responses to distractor change, no enhancements in encoding for the natural scenes are necessary or even expected. Yet these enhancements in stimulus discriminability occurred close to the anticipated stimulus change and were more pronounced in trials with short reaction times (Figure S1B). It is conceivable that these states are particularly favorable to permit refinement of stimulus representations by structured top-down signals, suggesting that in a different task context they may carry behavioral relevance.

In summary, we showed that the spatial allocation of attention towards a natural stimulus can engage mechanisms that exploit the higher order statistical regularities of natural images, resulting in enhanced decodability of neuronal population responses in area V1. The alignment between the attentional and natural stimulus variance in low-dimensional projections of V1 activity vectors, which was absent for synthetic low-level stimuli, suggests that attention can involve mechanisms optimized for the processing of natural images in order to refine stimulus representation in V1. These results highlight the importance of using natural stimuli when studying sensory processing and provide important insights into how such factors as natural image statistics and the animals' internal models of the visual world are central to visual processing even at early levels.

Materials and Methods

Electrophysiological Recordings. The data was obtained from two adult rhesus macaque monkeys, one male (monkey A) and one female (monkey I), aged 8 and 12 years, respectively, during the time of the study. All experimental procedures were approved by the local authorities (Regierungspräsidium, Hessen, Darmstadt, Germany) and were in accordance with the animal welfare guide-

lines of the European Union's Directive 2010/63/EU. Animals were housed in rooms with outdoor access to a play area and had regular veterinary care and balanced nutrition. The recording chamber was implanted under general anesthesia over the primary visual cortex, the exact location was determined based on stereotactic coordinates derived from MRI and CT scans.

Signals were recorded using a chronically implanted microdrive containing 32 independently movable glass-coated tungsten electrodes with impedance between 0.7 and 1.5 MΩ and 1.5 mm inter-electrode distance (SC32; Gray Matter Research (56)), amplified (TDT, PZ2 pre-amplifier) and digitized at a rate of 24.4 kHz. The signals were filtered between 300 and 4,000 Hz and a threshold was set at 4SD above noise level to extract multi-unit activity. LFP signals were obtained by low-pass filtering at 300 Hz and downsampling to 1.5 kHz.

Behavioral Paradigm. Animals were seated in a custom primate chair at a distance of 64 cm in front of a 477 × 298 mm monitor (Samsung SyncMaster 2233RZ; 120 Hz refresh rate). At the start of each recording week, the receptive fields and orientation preferences of the recorded units were mapped with a moving light bar drifting in a randomized sequence in eight different directions.

The two monkeys performed an attention-modulated change detection task. During the task, eye tracking was performed using an infrared-camera eye-control system (ET-49; Thomas Recording). To initiate a trial, the monkey maintained fixation on a white spot (0.1° visual angle) presented in the center of a black screen and pressed a lever. After 500 ms, two identical visual stimuli appeared in an aperture of 2.8–5.1° at a distance of 2.3–3.2° from the fixation point. One of the stimuli covered the receptive fields of the recorded units, which were situated in the right hemifield, the other stimulus was placed at the mirror symmetric site in the left hemifield. After an additional 700 ms, the fixation spot changed color, cuing the monkey to covertly direct its attention to one of the two stimuli. When the cued image was rotated (20°), the monkey released a lever in a fixed time window (600 ms for monkey A; 900 ms for monkey I) to receive a reward. A break in fixation (fixation window, 1.5° diameter) or an early lever release resulted in the abortion of the trial, which was announced by a tone signal. Breaks in fixation occurred less frequently in the time interval preceding an image rotation compared to the baseline (Figure S8A), and occurred with similar frequency irrespective of stimulus content (natural or control) or attentional condition (Figure S8B). Data analysis was based on completed correct trials (mean number per session 967 trials for monkey A; 720 trials for monkey I).

Visual Stimulus Design. Stimuli were static, black and white images, presented in a square or circular aperture. Within each recording session, all natural scenes and control images had equal luminance and contrast.

Control images were generated in two ways.

(1) Filter-scrambling: synthetic stimuli generated from an image model. Filter scrambling was realized by permuting Gabor filter activations elicited by a natural image across the elements of the complete filter bank. The filter bank was composed of a large set of Gabor functions, fitted to the receptive field (RF) characteristics of the recorded neurons. The positions and orientations of the Gabor functions covered the image uniformly, while their size was matched to the RFs of visual cortical neurons recorded at the same eccentricity. An activation variable determined the level of contribution of each particular Gabor function to the image. The synthetic images were generated by linearly combining the activation-scaled Gabor functions. For each synthetic image, the activations of 500–3,000 Gabor functions were sampled from the empirical distribution of Gabor filter responses to a particular natural image. The resulting control images lacked the higher-order structure of natural scenes but matched their low-level statistical properties.

(2) Phase-scrambled images. The 2D fast Fourier transform (FFT) of each natural image was computed to obtain a complex magnitude-phase map. The phase values were scrambled by assigning a random value to each element taken from a uniform distribution across the range $(-\pi, \pi)$. An inverse FFT was then applied to the resulting magnitude-phase maps to produce scrambled versions of the original natural images. These control images lacked the higher-order structure of natural scenes but matched their frequency spectrum.

In a second experiment, recorded in one monkey (monkey I), we contrasted synthetic stimuli with and without higher-order structure. These synthetic images were generated similarly to the control images described in (1) and matched the low-level statistical properties of natural scenes. To add higher-order structure, a subset of Gabor functions were arranged in a manner that produced simple contour-like patterns (example of contour synthetic image in Figure 3D).

Data analysis. Data analysis was performed using custom code in MATLAB (MathWorks) and the Fieldtrip toolbox (57).

We applied non-parametric statistical tests to avoid assumptions about the distributions of the empirical data. Information about sample variables and size is reported in the results section. Critical results and statistics are reported separately for individual animals in the supplementary materials.

Discriminability index. The *unit d'*, also known as Cohen's effect size (58), for a pair of stimuli, was calculated as:

$$d'_i = (m_1 - m_2)/\sigma \quad \textbf{(1)}$$

where m_1 and m_2 are the mean spike-counts across trials of unit i to the two stimuli and $\sigma = (\sigma_1 + \sigma_2)/2$ is the mean standard deviation. The *population d'* was calculated similarly, except in this case m_1, m_2 and σ are n-dimensional vectors of spike-counts, where n is the number of simultaneously recorded units in a session. Distances in vector space were calculated using the Euclidean distance.

Cross-validated PCA and stimulus decoding. PCA was applied on population spike-count vectors calculated over a 200 ms time window in the trial, $1700 - 1900$ ms after stimulus onset. We performed cross-validation by randomly subsampling the data ($k-1$ data partitions used for training, 1 used for test, k repetitions; $k = 5$). This meant that, for each recording session and each pair of natural stimuli, we ran PCA $k = 5$ times, on each iteration randomly sampling the population response to the two stimuli. Trials for both attentional conditions were included in the construction of the PCA space. For stimulus classification, trials belonging to the attention in/out conditions were separated. For each attentional condition, separately, 16 Naïve Bayes classifiers were trained to decode the stimulus identity based on data points mapped in the space described by the first k principal components, with $k = 1$ to 16. The unseen trials were then projected in the same space to assess test performance. The performance values reported in Figure 3B are mean validation scores pulled across all stimulus pairs and all recording sessions. Chance level was 50 %.

The control stimuli and contour stimuli were analyzed separately, in a similar manner. Thus, the projection space obtained via PCA was different for natural scenes and control stimuli. A comparison of the percentage of variance explained by an increasing number of principal components, for natural scenes and controls recorded in the same sessions, can be found in Figure S5.

To enquire whether stimulus decoders benefit from knowledge on correlated variability across trials, stimulus classification for variable numbers of PCs was compared for shuffled and unshuffled data in Figure S5. In this case, shuffling was performed across trials, within each stimulus condition (i.e. signal correlations were not affected), after the construction of the PCA projection space, but before the training of the Bayesian classifier. Test data was unshuffled, so that the distribution of original spike-counts was not affected.

LFP analysis. Power spectra were computed using a frequency-dependent window length (5 cycles per time window). This approach decreases the temporal smoothing at higher frequencies and increases the sensitivity to brief effects. The time-windows were moved in steps of 10 ms and Hann-tapered to avoid spectral leakage.
Data presented in Figure 4A shows LFP power after the substraction of the prestimulus baseline.

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1. Hermann von Helmholtz. *Handbuch der physiologischen Optik*. Voss, 1867.
2. W. Singer and F. Tretter. Unusually large receptive fields in cats with restricted visual experience. *Experimental Brain Research*, 26(2):171–184, September 1976. ISSN 0014-4819, 1432-1106. doi: 10.1007/BF00238281.
3. Pietro Berkes, Gergő Orbán, Máté Lengyel, and József Fiser. Spontaneous cortical activity reveals hallmarks of an optimal internal model of the environment. *Science*, 331(6013): 83–87, 2011. ISSN 0036-8075. doi: 10.1126/science.1195870.
4. Mihály Bányai, Andreea Lazar, Liane Klein, Johanna Klon-Lipok, Marcell Stippinger, Wolf Singer, and Gergő Orbán. Stimulus complexity shapes response correlations in primary visual cortex. *Proceedings of the National Academy of Sciences*, 116(7):2723–2732, 2019. ISSN 0027-8424. doi: 10.1073/pnas.1816766116.
5. R. Wurtz and C. W. Mohler. Enhancement of visual responses in monkey striate cortex and frontal eye fields. *Journal of Neurophysiology*, 39 4:766–72, 1976.
6. P. E. Haenny and P. H. Schiller. State dependent activity in monkey visual cortex. *Experimental Brain Research*, 69:225–244, 2004.
7. J. Duncan. Selective attention and the organization of visual information. *Journal of experimental psychology. General*, 113 4:501–17, 1984.
8. Pieter R. Roelfsema, Victor A. F. Lamme, and Henk Spekreijse. Object-based attention in the primary visual cortex of the macaque monkey. *Nature*, 395(6700):376–381, September 1998. ISSN 1476-4687. doi: 10.1038/26475.
9. Demetrio Ferro, Jochem van Kempen, Michael Boyd, Stefano Panzeri, and Alexander Thiele. Directed information exchange between cortical layers in macaque v1 and v4 and its modulation by selective attention. *Proceedings of the National Academy of Sciences*, 118(12), 2021. ISSN 0027-8424. doi: 10.1073/pnas.2022097118.
10. Christoph Kayser, Rodrigo F Salazar, and Peter Konig. Responses to natural scenes in cat v1. *Journal of neurophysiology*, 90(3):1910–1920, 2003.
11. Emmanouil Froudarakis, Philipp Berens, Alexander S Ecker, R James Cotton, Fabian H Sinz, Dimitri Yatsenko, Peter Saggau, Matthias Bethge, and Andreas S Tolias. Population code in mouse v1 facilitates readout of natural scenes through increased sparseness. *Nature neuroscience*, 17(6):851–857, 2014.
12. Cem Uran, Alina Peter, Andreea Lazar, William Barnes, Johanna Klon-Lipok, Katharine A. Shapcott, Rasmus Roese, Pascal Fries, Wolf Singer, and Martin Vinck. Predictive coding of natural images by v1 firing rates and rhythmic synchronization. *Neuron*, 110(7):1240–1257.e8, 2022. ISSN 0896-6273. doi: https://doi.org/10.1016/j.neuron.2022.01.002.
13. Phillip Pope, Chen Zhu, Ahmed Abdelkader, Micah Goldblum, and Tom Goldstein. The intrinsic dimension of images and its impact on learning. *arXiv preprint arXiv:2104.08894*, 2021.
14. Eero P Simoncelli and Bruno A Olshausen. Natural image statistics and neural representation. *Annual review of neuroscience*, 24(1):1193–1216, 2001.
15. Jay Hegdé and David C. Van Essen. Temporal dynamics of shape analysis in macaque visual area v2. *Journal of Neurophysiology*, 92(5):3030–3042, 2004. doi: 10.1152/jn.00822.2003. PMID: 15201315.
16. Narihisa Matsumoto, Masato Okada, Yasuko Sugase-Miyamoto, Shigeru Yamane, and Kenji Kawano. Population dynamics of face-responsive neurons in the inferior temporal cortex. *Cerebral cortex*, 15 8:1103–12, 2005.
17. Andreea Lazar, Christopher Lewis, Pascal Fries, Wolf Singer, and Danko Nikolic. Visual exposure enhances stimulus encoding and persistence in primary cortex. *Proceedings of the National Academy of Sciences*, 118(43), 2021. ISSN 0027-8424. doi: 10.1073/pnas.2105276118.
18. Carsen Stringer, Marius Pachitariu, Nick Steinmetz, Matteo Carandini, and Kenneth Harris. High-dimensional geometry of population responses in visual cortex. *Nature*, pages 361–365, 06 2019. doi: 10.1101/374090.
19. Nicolas Brunet, Conrado A. Bosman, Mark Roberts, Robert Oostenveld, Thilo Womelsdorf, Peter De Weerd, and Pascal Fries. Visual Cortical Gamma-Band Activity During Free Viewing of Natural Images. *Cerebral Cortex*, 25(4):918–926, 10 2013. ISSN 1047-3211. doi: 10.1093/cercor/bht280.
20. Stefan Treue. Visual attention: the where, what, how and why of saliency. *Current opinion in neurobiology*, 13(4):428–432, 2003.
21. Guy A Orban. Higher order visual processing in macaque extrastriate cortex. *Physiological reviews*, 2008.
22. R Quian Quiroga, Leila Reddy, Gabriel Kreiman, Christof Koch, and Itzhak Fried. Invariant visual representation by single neurons in the human brain. *Nature*, 435(7045):1102–1107, 2005.
23. Siegrid Löwel and Wolf Singer. Selection of intrinsic horizontal connections in the visual cortex by correlated neuronal activity. *Science*, 255(5041):209–212, 1992.
24. Charles G Gross, CE de Rocha-Miranda, and DB Bender. Visual properties of neurons in inferotemporal cortex of the macaque. *Journal of neurophysiology*, 35(1):96–111, 1972.
25. Toshiyuki Hirabayashi, Daigo Takeuchi, Keita Tamura, and Yasushi Miyashita. Microcircuits for hierarchical elaboration of object coding across primate temporal areas. *Science*, 341 (6142):191–195, 2013.
26. Minggui Chen, Yin Yan, Xiajing Gong, Charles D Gilbert, Hualou Liang, and Wu Li. Incremental integration of global contours through interplay between visual cortical areas. *Neuron*, 82(3):682–694, 2014.
27. Hualou Liang, Xiajing Gong, Minggui Chen, Yin Yan, Wu Li, and Charles D Gilbert. Interactions between feedback and lateral connections in the primary visual cortex. *Proceedings of the National Academy of Sciences*, 114(32):8637–8642, 2017.
28. James J Knierim and David C Van Essen. Neuronal responses to static texture patterns in area v1 of the alert macaque monkey. *Journal of neurophysiology*, 67(4):961–980, 1992.
29. Andrew F Rossi, Cynthia D Rittenhouse, and Michael A Paradiso. The representation of brightness in primary visual cortex. *Science*, 273(5278):1104–1107, 1996.
30. Julia Biederlack, Miguel Castelo-Branco, Sergio Neuenschwander, Diek W. Wheeler, Wolf Singer, and Danko Nikolić. Brightness induction: Rate enhancement and neuronal synchronization as complementary codes. *Neuron*, 52(6):1073–1083, 2006. ISSN 0896-6273. doi: https://doi.org/10.1016/j.neuron.2006.11.012.
31. Mitesh K Kapadia, Minami Ito, Charles D Gilbert, and Gerald Westheimer. Improvement in visual sensitivity by changes in local context: parallel studies in human observers and in v1 of alert monkeys. *Neuron*, 15(4):843–856, 1995.
32. Betram R Payne, Stephen G Lomber, Alessandro E Villa, and Jean Bullier. Reversible deactivation of cerebral network components. *Trends in neurosciences*, 19(12):535–542, 1996.
33. Victor AF Lamme, Hans Super, and Henk Spekreijse. Feedforward, horizontal, and feedback processing in the visual cortex. *Current opinion in neurobiology*, 8(4):529–535, 1998.
34. Victor A.F. Lamme and Pieter R. Roelfsema. The distinct modes of vision offered by feedforward and recurrent processing. *Trends in Neurosciences*, 23(11):571–579, 2000. ISSN 0166-2236. doi: https://doi.org/10.1016/S0166-2236(00)01657-X.
35. Jacqueline R Hembrook-Short, Vanessa L Mock, and Farran Briggs. Attentional modulation of neuronal activity depends on neuronal feature selectivity. *Current Biology*, 27(13):1878–1887, 2017.
36. John Duncan, Glyn Humphreys, and Robert Ward. Competitive brain activity in visual attention. *Current opinion in neurobiology*, 7(2):255–261, 1997.
37. Marlene R Cohen and John HR Maunsell. Using neuronal populations to study the mechanisms underlying spatial and feature attention. *Neuron*, 70(6):1192–1204, 2011.
38. Roger BH Tootell, Nouchine Hadjikhani, E Kevin Hall, Sean Marrett, Wim Vanduffel, J Thomas Vaughan, and Anders M Dale. The retinotopy of visual spatial attention. *Neuron*, 21(6):1409–1422, 1998.
39. Narcisse P Bichot, Andrew F Rossi, and Robert Desimone. Parallel and serial neural mechanisms for visual search in macaque area v4. *Science*, 308(5721):529–534, 2005.
40. Anne Treisman. The perception of features and objects. *Visual attention*, 8:26–54, 1998.
41. James A Mazer. Spatial attention, feature-based attention, and saccades: three sides of one coin? *Biological psychiatry*, 69(12):1147–1152, 2011.
42. Erin Goddard, Thomas A Carlson, and Alexandra Woolgar. Spatial and feature-selective attention have distinct, interacting effects on population-level tuning. *Journal of cognitive neuroscience*, 34(2):290–312, 2022.
43. George A. Alvarez and Aude Oliva. Spatial ensemble statistics are efficient codes that can be represented with reduced attention. *Proceedings of the National Academy of Sciences*, 106(18):7345–7350, 2009. doi: 10.1073/pnas.0808981106.
44. Jeffrey Moran and Robert Desimone. Selective attention gates visual processing in the extrastriate cortex. *Science*, 229(4715):782–784, 1985.
45. David L Sheinberg and Nikos K Logothetis. The role of temporal cortical areas in perceptual organization. *Proceedings of the National Academy of Sciences*, 94(7):3408–3413, 1997.
46. A. M. Ni, D. A. Ruff, J. J. Alberts, J. Symmonds, and M. R. Cohen. Learning and attention reveal a general relationship between population activity and behavior. *Science*, 359(6374): 463–465, 2018. ISSN 0036-8075. doi: 10.1126/science.aao0284.
47. Andreas K Engel and Pascal Fries. Beta-band oscillations—signalling the status quo? *Current opinion in neurobiology*, 20(2):156–165, 2010.
48. Georgios Spyropoulos, Conrado Arturo Bosman, and Pascal Fries. A theta rhythm in macaque visual cortex and its attentional modulation. *Proceedings of the National Academy of Sciences*, 115(24):E5614–E5623, 2018.
49. N Kopell, GB Ermentrout, Miles A Whittington, and Roger D Traub. Gamma rhythms and beta rhythms have different synchronization properties. *Proceedings of the National Academy of Sciences*, 97(4):1867–1872, 2000.
50. Irene Onorato, Sergio Neuenschwander, Jennifer Hoy, Bruss Lima, Katia-Simone Rocha, Ana Clara Broggini, Cem Uran, Georgios Spyropoulos, Johanna Klon-Lipok, Thilo Wom-

elsdorf, et al. A distinct class of bursting neurons with strong gamma synchronization and stimulus selectivity in monkey v1. *Neuron*, 105(1):180–197, 2020.

51. Christopher Murphy Lewis, Jianguang Ni, Thomas Wunderle, Patrick Jendritza, Andreea Lazar, Ilka Diester, and Pascal Fries. Cortical gamma-band resonance preferentially transmits coherent input. *Cell Reports*, 35(5):109083, 2021. ISSN 2211-1247. doi: https://doi.org/10.1016/j.celrep.2021.109083.
52. Alina Peter, Cem Uran, Johanna Klon-Lipok, Rasmus Roese, Sylvia van Stijn, William Barnes, Jarrod R Dowdall, Wolf Singer, Pascal Fries, and Martin Vinck. Surface color and predictability determine contextual modulation of v1 firing and gamma oscillations. *Elife*, 8: e42101, 2019.
53. Thilo Womelsdorf, Pascal Fries, Partha P Mitra, and Robert Desimone. Gamma-band synchronization in visual cortex predicts speed of change detection. *Nature*, 439(7077):733–736, 2006.
54. Demetrio Ferro, Jochem van Kempen, Michael Boyd, Stefano Panzeri, and Alexander Thiele. Directed information exchange between cortical layers in macaque v1 and v4 and its modulation by selective attention. *Proceedings of the National Academy of Sciences*, 118(12):e2022097118, 2021.
55. Matthew Chalk, Jose L Herrero, Mark A Gieselmann, Louise S Delicato, Sascha Gotthardt, and Alexander Thiele. Attention reduces stimulus-driven gamma frequency oscillations and spike field coherence in v1. *Neuron*, 66(1):114–125, 2010.
56. David A Markowitz, Yan T Wong, Charles M Gray, and Bijan Pesaran. Optimizing the decoding of movement goals from local field potentials in macaque cortex. *Journal of Neuroscience*, 31(50):18412–18422, 2011.
57. R. Oostenveld, P. Fries, E. Maris, and J. Schoffelen. Fieldtrip: Open source software for advanced analysis of meg, eeg, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, 2011.
58. J Cohen. Statistical power analysis for the behavioral sciences., 1988.

Supplementary Materials

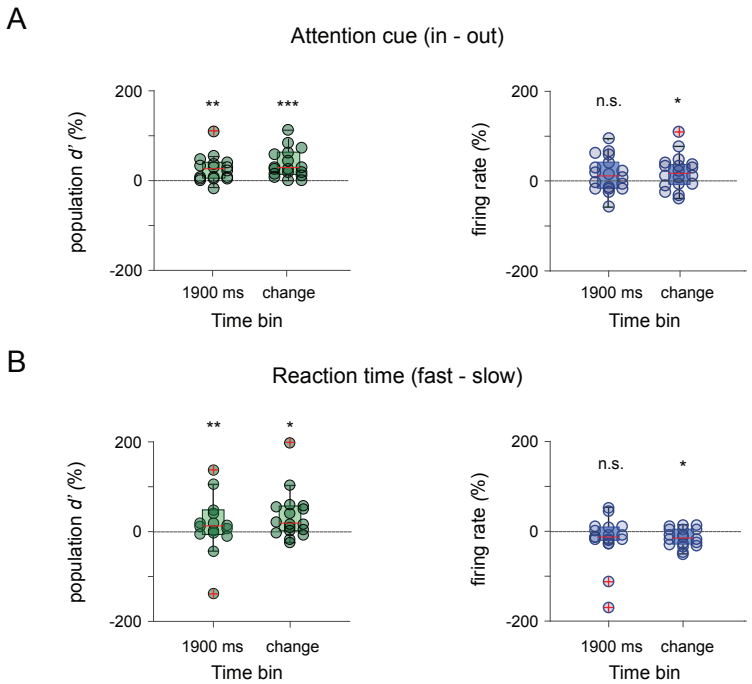

Fig. S1. Attentional changes in neuronal population responses. A) Population discriminability index d' (left) and population firing rates (right) shown as percentage increase between the *attention-in* and *attention-out* conditions. Circles represent independent recording sessions. The box-plots correspond to two time windows in the trial (1700-1900 ms and the 200 ms window before the stimulus change). Changes in population d' with attention were strongly significant in both windows (Wilcoxon signed-rank test; 1700-1900 ms: P = 0.0012; change-aligned: P = 0.00023; n = 18 sessions). Firing rates increased significantly for the change-aligned data (Wilcoxon signed-rank test; 1700-1900 ms: P = 0.1330 *n.s.*; change-aligned: P = 0.0279; n = 18 sessions). B) Comparison of population d' and population firing rates as a function of reaction time (RT) to the stimulus change. Trials corresponding to the *attention-in* condition, were sorted based on RT, separately for each stimulus condition, and split in two halves referred to as *fast-RT* and *slow-RT*. We found that the population discriminability index was higher for fast RT compared to slow RT (Wilcoxon signed-rank test; 1700-1900 ms: P = 0.0043 ; change-aligned: P = 0.0123; n = 18 sessions). Population firing rates were significantly lower for the change-aligned data (Wilcoxon signed-rank test; 1700-1900 ms: P = 0.6791 *n.s.*. ; change-aligned: P = 0.0347; n = 18 sessions). Note that the results from the subplots in B were based on approximately half the number of trials from the subplots in A.

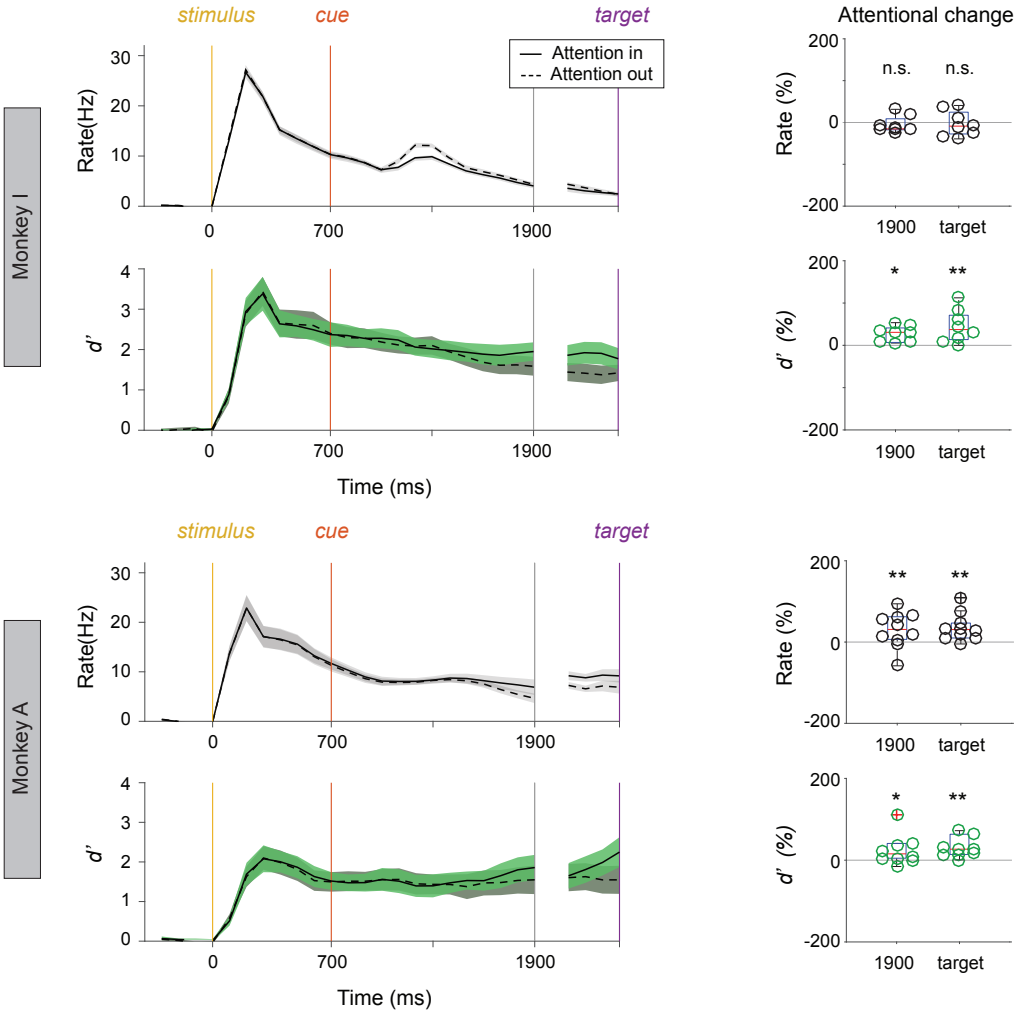

Fig. S2. Firing rate responses and discriminability index d' in individual animals. Responses are shown over the course of the trial: spike-counts were calculated over 200 ms windows with 100 ms sliding resolution. Population firing rates (blue) increased significantly with attention, before the target event, in one monkey (right panels, blue; Wilcoxon signed-rank test; 1700-1900 ms: P = 0.46 n.s.; target-aligned: P = 0.64 n.s.; n = 8 sessions Monkey I; 1700-1900 ms: P = 0.009; target-aligned: P = 0.0039; n = 10 sessions Monkey A). Population d' (green) increased significantly with attention, before the target event, in both monkeys (right panels, green; Wilcoxon signed-rank test; 1700-1900 ms: P = 0.0078; target-aligned: P = 0.0156; n = 8 sessions Monkey I; 1700-1900 ms: P = 0.04; target-aligned: P = 0.002; n = 10 sessions Monkey A). Shading marks standard error from the mean. Right panels show changes with attention in all individual recording sessions for data aligned on both stimulus onset and target.

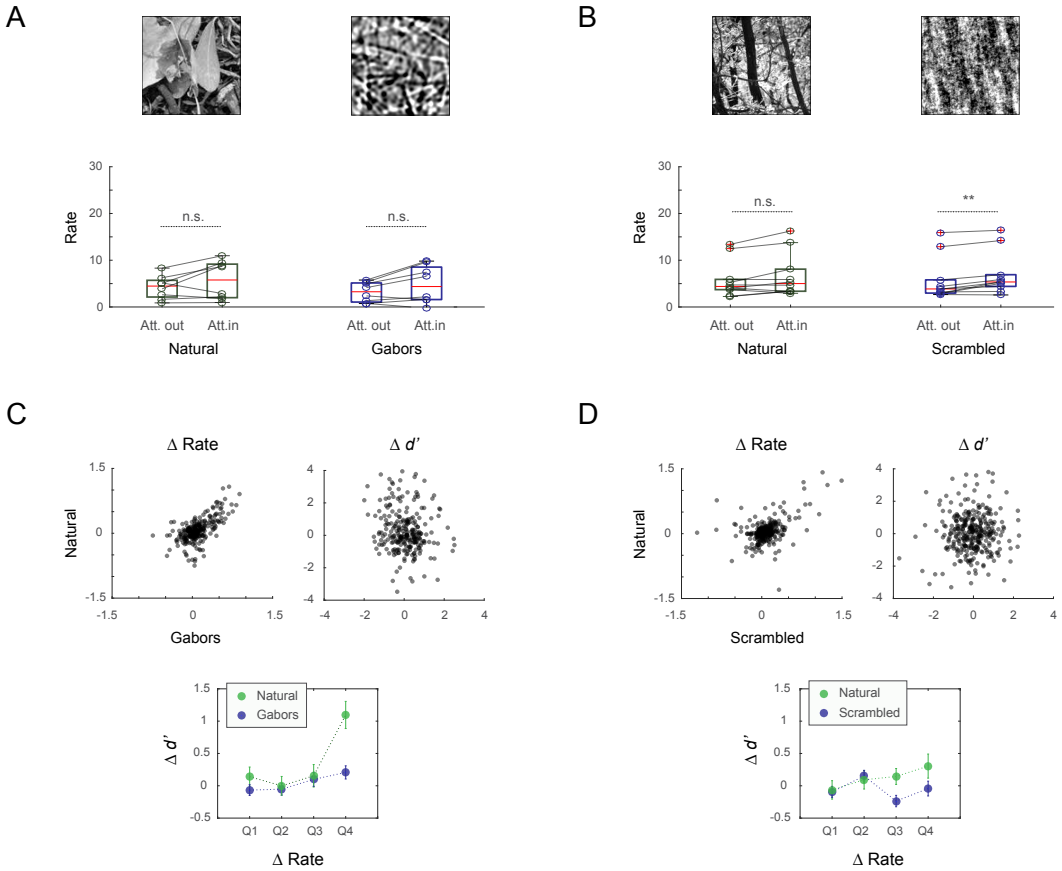

Fig. S3. Firing rate responses are modulated by attention similarly for natural scenes and synthetic controls (A) Firing rate responses for both natural scenes and synthetic gabors increase modestly with attention, however the increase is not significant (Wilcoxon signed-rank test; change-aligned; natural-scenes P = 0.1484; gabors P = 0.0781; n = 8 sessions, 2 monkeys). (B) Firing rate responses for natural scenes and scrambled controls increase modestly with attention. The increase is only significant for the controls (Wilcoxon signed-rank test; change-aligned; natural-scenes P = 0.084 n.s.; scrambled P = 0.0039; n = 10 sessions, 2 monkeys). C) Firing rate changes with attention for natural scenes and synthetic gabors are positively correlated across units (values are z-scored per session); changes in d' are not (Spearman's rank correlation; firing rate r= 0.58, p = 2.4e-24; d' r= -0.16, p = 0.009). D) As in C, firing rate changes with attention for natural scenes and scrambled scenes are positively correlated across units; changes in d' are not (Spearman's rank correlation; firing rate r= 0.35, p = 1.1e-10; d' r= 0.009, p = 0.87). Bottom panels: change in d' as a function of change in firing rate with attention. Units are sorted by amplitude of rate change and grouped into quartiles (marked on x-axis). d' values on y-axis are z-scored per session. Large increases in firing rates with attention (4th quartile) result in a larger positive changes in d' for natural stimuli (green), compared to controls (blue). Error bars indicate standard errors from the mean.

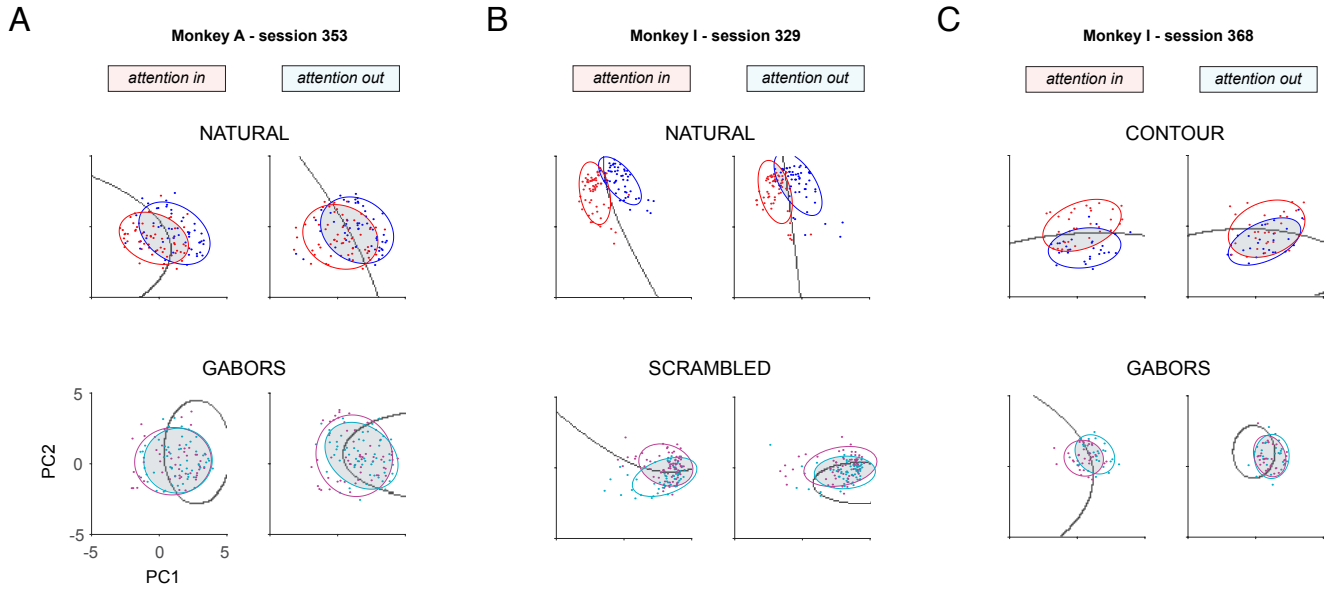

Fig. S4. Effects of attention on stimulus encoding in principal component space Three example sessions (A, B and C), contrasting pairs of natural stimuli and contour stimuli (upper panels), to synthetic controls (bottom panels). Individual points represent trials, each point is a spike-count vector over the 1700-1900 ms interval projected in PCA space. As in Figure 3, the PCA space was constructed based on pre-cue activity (500-700 ms). Ellipses were fit to encompass responses within one standard deviation from the mean. Gray lines show boundaries of Bayesian decoders. For natural scenes and contour stimuli, overlap between the population responses is lower in the *attention-in* condition. Thus the attentional effects can be observed already from a low number of principal components, suggesting an alignment between attentional and stimulus variance.

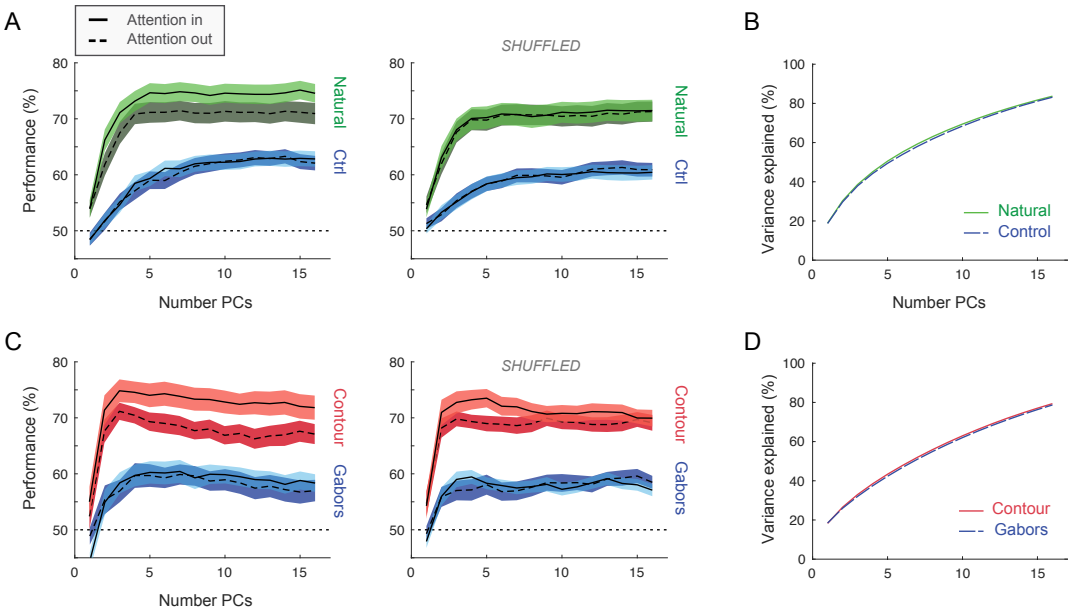

Fig. S5. Effect of trial-shuffling on stimulus decoding in PCA space (A) Decoding performance of natural scenes (green) and control stimuli (blue) based on spike-count vectors over the 1700-1900 ms interval in principal component space, for a variable number of PCs (x-axis). As in Figure 3, the PCA space was constructed separately for natural scenes and controls, based on pre-cue activity (500-700 ms, see more details in Methods). Original data (left; n = 71 stimulus pairs; 18 recording sessions) is contrasted to trial-shuffled data (right). Shuffling removes correlations across trials, i.e. the so called noise correlations or spike-count correlations. Shuffling affected the fit of the Bayesian classifier, not the construction of the PCA space, and was performed only on training data, not on test data. Shaded areas indicate standard error of the mean. (B) Variance explained by an increasing number of principal components is similar for PCA spaces constructed separately for natural scenes and controls. These PCA spaces are identical for shuffled data, since shuffling was only applied before training the classifier. (C) Similar to A for contour stimuli and gabor controls (example stimuli in Figure 3) (D) similar to B for contour stimuli and gabor controls (n = 30 stimulus pairs; 5 recording sessions). In A and C, attentional effects can be observed already from a low number of principal components, for natural scenes (green) and contour stimuli (red), but are absent for the synthetic controls (blue) and are reduced by shuffling (right panels). In B and D, variance explained is almost identical for PCA spaces constructed for natural stimuli/contour stimuli and their respective control counterparts

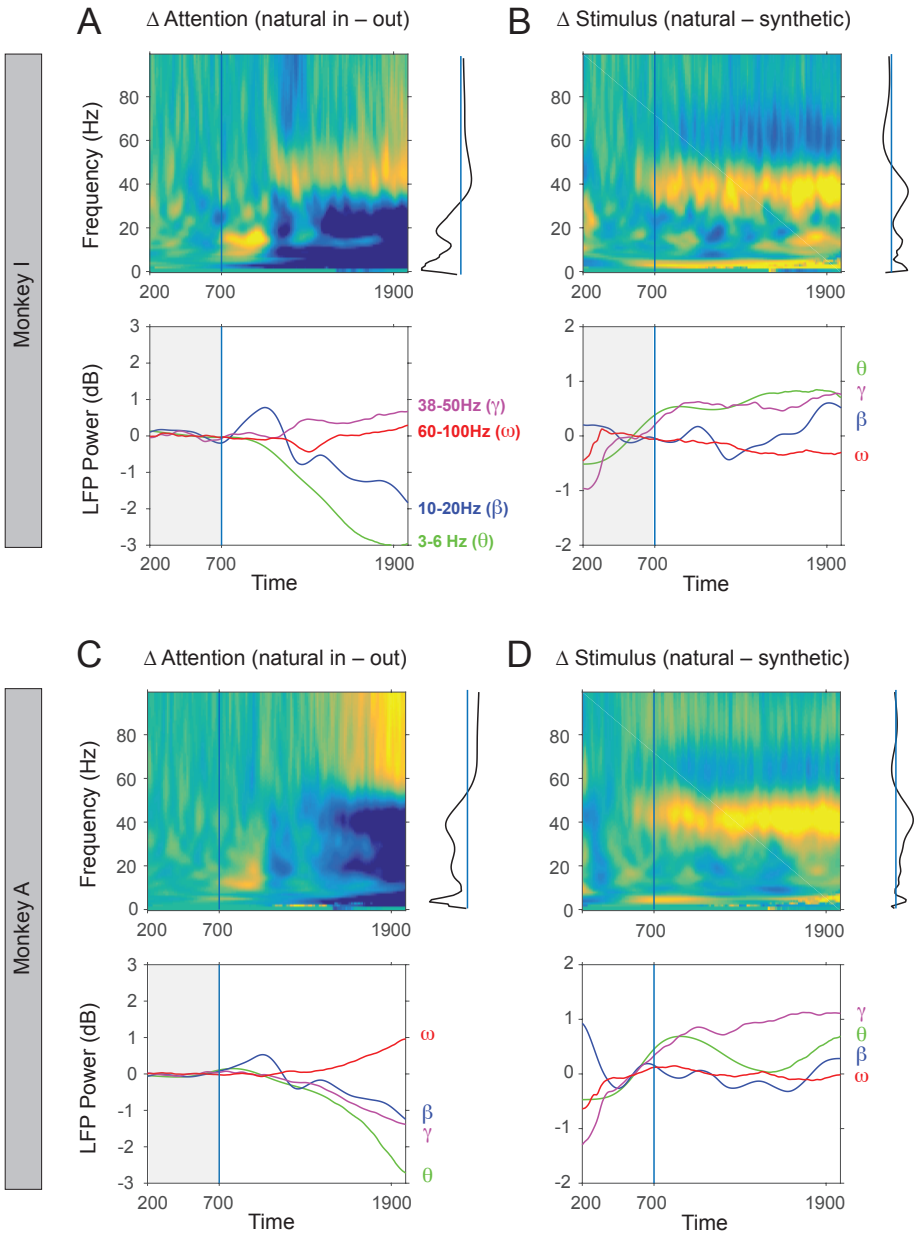

Fig. S6. Trial dynamics of LFP power spectra in two monkeys (upper and lower panels) (A) Attentional differences in time-frequency log-transformed LFP power in monkey I (top-panel, 8 recording sessions). The arrival of the attentional cue at 700 ms is marked by vertical line. Right-side projection shows attentional modulation of LFP power for the 1700-1900 ms time window. Attentional differences in LFP power in 4 frequency bands for natural stimuli (bottom panel, 500 ms pre-cue baseline was substracted). In this monkey, the LFP power at frequencies >38Hz increased with attention, while the LFP power at frequencies <38Hz decreased with attention. (B) Differences in LFP power between natural scenes and synthetic images. 500 ms pre-cue baseline was substracted to emphasize post-cue effects. LFP power in the gamma (38-50Hz) and theta (3-6Hz) ranges was stronger for natural stimuli compared to their synthetic counterparts. (C) Attentional differences in LFP power for monkey A (top, time-frequency plot; bottom, power in 4 bands; 8 recording sessions). In this monkey, the LFP power at frequencies >50Hz increased with attention, while the LFP power at frequencies <50Hz decreased with attention. (D) Differences in LFP power between natural and synthetic stimuli for monkey A (top, time-frequency plot; bottom, power in 4 bands; 8 recording sessions). Similarly to the plots in (B) for monkey I, natural stimuli produced more gamma and more theta compared to the synthetic controls in monkey A.

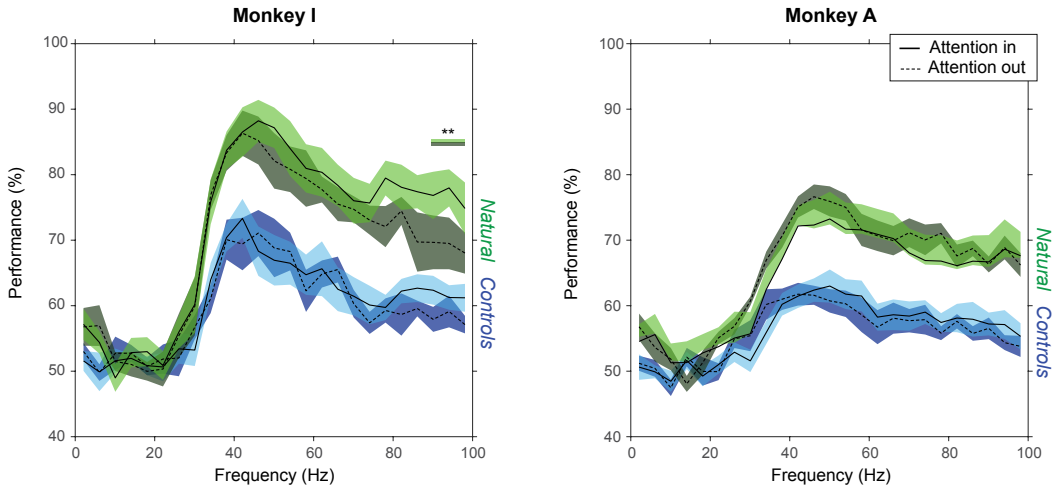

Fig. S7. Decoding of stimulus identity based on LFP responses in individual animals. Bayesian classifiers were used to decode the identity of a stimulus based on single trial LFP data (monkey I left, n = 8 sessions, monkey A right, n = 10 sessions; 1700-1900ms time-window). In each recording session the LFP power of all channels (maximum 32) for 4 consecutive frequencies (1-4Hz, 5-8Hz.. 96-100Hz) were concatenated, resulting in data vectors of length < 4x32. Performance is shown separately for natural scenes (green) and control images (blue), for all 25 frequency intervals (x-axis). In both monkeys, classification of natural scenes was significantly above chance level and above the classification performance of control images, for frequencies higher than 40Hz (10-fold validation, chance level 50%). There was no attentional effect on stimulus decoding based on LFP power, except at the highest frequencies in monkey I (88-91Hz ,92-95Hz, 96-100Hz, significant intervals marked by green bar).

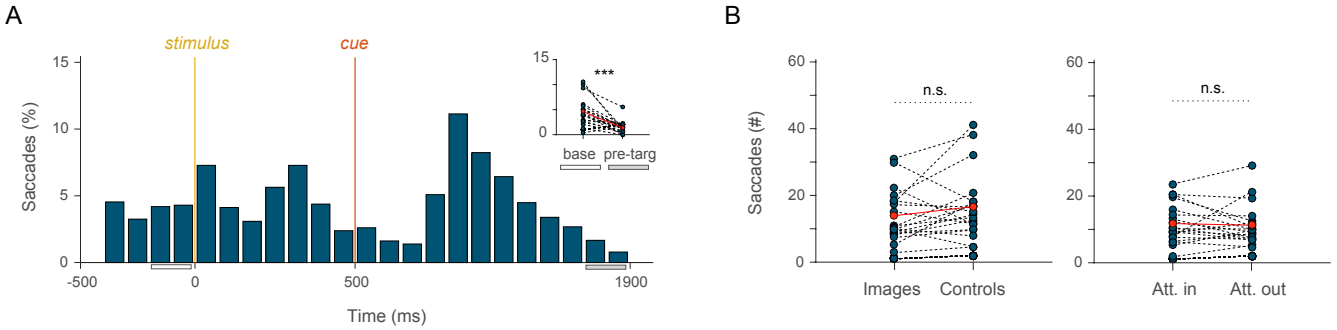

Fig. S8. Eye movements during the task (A) Frequency of saccadic eye movements along the trial. The time window preceding the stimulus change (1700-1900ms), in which the effects of visual attention were strong, corresponds to a period with reduced eye movements compared to the baseline (statistics in inset panel: Wilcoxon signed-rank test, 1700-1900 ms, P = 0.00019, n = 18 sessions in 2 monkeys). (B) Saccades towards natural stimuli and controls occurred in similar numbers (left panel; Wilcoxon signed-rank test, post-cue time interval 500-1900ms, P = 0.171 n.s.). Saccades towards attended and unattended stimuli occurred in similar numbers (right panel; Wilcoxon signed-rank test; 500-1900ms; P = 0.522 n.s.).