Similar adaptation effects in primary visual cortex and area MT of the macaque monkey under matched stimulus conditions

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Abstract

Recent stimulus history, or adaptation, can alter neuronal response properties. Adaptation effects have been characterized in a number of visually-responsive structures, from the retina to higher visual cortex. However, it remains unclear whether adaptation effects across stages of the visual system take a similar form in response to a particular sensory event. This is because studies typically probe a single structure or cortical area, using a stimulus ensemble chosen to provide potent drive to the cells of interest. Here we adopt an alternative approach, and compare adaptation effects in primary visual cortex (V1) and area MT using identical stimulus ensembles. Previous work has suggested these areas adjust to recent stimulus drive in distinct ways. We show that this is not the case: adaptation effects in V1 and MT can involve weak or strong loss of responsivity and shifts in neuronal preference toward or away from the adapter, depending on stimulus size and adaptation duration. For a particular stimulus size and adaptation duration, however, effects are similar in nature and magnitude in V1 and MT. We also show that adaptation effects in MT of awake animals depend strongly on stimulus size. Our results suggest that the strategies for adjusting to recent stimulus history depend more strongly on adaptation duration and stimulus size, than on the cortical area. Moreover, they indicate that different levels of the visual processing cascade adapt similarly to recent sensory experience.

Keywords: surround suppression, adaptation duration, motion processing, plasticity
Adaptation – the stimulus history of the preceding hundreds of milliseconds to minutes – can profoundly change neuronal response properties. Adaptation effects have been characterized in the retina (e.g. Brown and Maslund, 2001; Baccus and Meister, 2002; Chander and Chichilnisky, 2001; Rieke, 2001; Zaghloul et al., 2005), the lateral geniculate nucleus (LGN; e.g. Solomon et al., 2004; Camp et al., 2009; McLelland et al., 2009), primary visual cortex (e.g. Movshon and Lennie, 1989; Ohzawa et al., 1985; Carandini et al., 1997; Muller et al., 1999; Dragoi et al., 2000; Felsen et al., 2002; Crowder et al., 2006; Ghisovan et al., 2009; Wissig and Kohn, 2012), area MT (e.g. Van Wezel and Britten, 2002; Kohn and Movshon, 2004; Krekelberg et al., 2006; Yang and Lisberger, 2009), and in inferotemporal cortex (e.g. Sawamura et al., 2006; Liu et al., 2009), among many others (see Kohn, 2007; Webster 2011 for recent reviews).

These studies have provided a rich description of how cortical circuits adjust to recent visual input, but they have left unclear how a particular sensory event alters the distributed representation of information in the visual system. This is because studies, understandably, have focused on measuring effects with stimuli that are most appropriate for driving the structure of interest: for instance, flickering checkerboards in the retina or images of objects in inferotemporal cortex. As a result, it remains unclear whether different networks have similar strategies for adjusting to a particular recent input.

Several studies have attempted to discern whether changes in sensitivity measured in one network could be explained by effects inherited from earlier areas or structures (Movshon and Lennie, 1979; Ohzawa et al., 1985; Nelson, 1991a,b; Priebe et al., 2002; Kohn and Movshon, 2003). However, these have focused on changes in responsivity (or contrast sensitivity) to a single stimulus, and not probed whether tuning is altered in a similar way at successive stages of processing. Changes in tuning are critical as they indicate how neuronal resources are allocated to represent the external environment. Further, even when adaptation effects are thought to be inherited from earlier areas, this does not dictate that the altered representation in the recipient area mirrors that in the source area. This is because adaptation-induced changes in the feedforward input to an area can alter the interactions among neurons there, so that tuning is affected in distinct ways in the source and target area (Kohn and Movshon, 2004; Compte et al., 2006).

Here we provide a straightforward comparison between adaptation effects on orientation and direction tuning in primary visual cortex (V1) and area MT, using identical stimulus ensembles in the two areas. V1 and MT are attractive targets for comparison because they are part of a well-studied motion processing pathway (Born and Bradley, 2005). In addition, previous work has suggested that neurons in these two areas adapt differently. In V1, adaptation effects involve stimulus-specific suppression. As a result, an adapter that falls on the flank of a neuron’s tuning curve will cause its preference to shift away from the adapter (Muller et al., 1999; Dragoi et al., 2000; Felsen et al., 2005). In MT, on the other hand, responsivity is reduced most strongly for stimuli that differ from the adapter. As a result, tuning shifts toward the adapter (Kohn and Movshon, 2004; Krekelberg et al., 2006; Schlack et al., 2007).

The observation that V1 and MT tuning are altered in a qualitatively different manner suggests distinct strategies for adjusting to recent stimulus history in these two networks. However, recent work offers an alternative interpretation. Wissig and Kohn (2012) showed that adaptation could cause either stimulus-specific suppression of V1 responses, when the adapter and test stimuli were small; or it could cause “MT-like” effects, when stimuli were large. The proposed mechanism is a stimulus-specific reduction in surround suppression following adaptation with a large stimulus. This reduces the suppressive influence recruited by test stimuli that extend beyond the classical receptive field (Cavanaugh et al., 2002; Angelucci and Bresslof, 2006).
reduction of surround suppression is a form of disinhibition, and can thus enhance responsivity and cause tuning to shift toward the adapter. Patterson et al. (2013) showed that the size-dependence of adaptation effects was evident after prolonged (40 s) but not brief (0.4 s) adaptation. As a result, V1 shows a broad range of adaptation effects, depending on stimulus size and adaptation duration.

Building on these observations, we sought to test whether MT effects mirror those in V1, for brief and prolonged adaptation with small and large grating stimuli. We find that, for each choice of stimulus parameters, effects in MT are similar in nature and magnitude to those in V1. We also show that adaptation effects in MT of an awake monkey are strongly modulated by stimulus size. Our results suggest that tuning in V1 and MT are affected similarly by recent visual experience.
Materials and Methods

All procedures were approved by the Institutional Animal Care and Use Committee of the Albert Einstein College of Medicine at Yeshiva University (anesthetized animals) or the Rutgers University Animal Care and Use Committee (awake animals) and were in compliance with the guidelines set forth in the United States Public Health Service Guide for the Care and Use of Laboratory Animals.

Surgical preparation (anesthetized): Monkeys (Macaca fascicularis) were given 0.05 mg/kg atropine and 1.5 mg/kg diazepam before surgery. Ketamine (10 mg/kg) was used to induce anesthesia. Monkeys were then intubated and started on 1.0-2.5% isoflurane in a 98% O2 / 2% CO2 mixture. Intravenous catheters were inserted into the saphenous vein of each leg and the animals were positioned in a stereotaxic device. A craniotomy and durotomy were performed to expose the underlying cortex. Once electrodes had been inserted, the opening was covered with agar to prevent desiccation. During recordings, isoflurane was discontinued and sufentanil citrate (6-24µg/kg/hr) was administered intravenously to maintain anesthesia; the paralytic vecuronium bromide (0.15 mg/kg/hr) was infused to prevent eye movements. Vital signs including ECG, EEG, blood pressure, SpO2, end-tidal PCO2, airway pressure, and temperature were monitored continuously. The corneas were protected with permeable contact lenses, and topical atropine was applied to dilate the pupils. Corrective lenses were used to focus the visual image.

Surgical preparation (awake): Recordings were performed in one macaque monkey (Macaca mulatta). Headposts and recording chambers were implanted under full isoflurane anesthesia in an aseptic environment. A recording chamber (high-density polyethylene; 25.3 mm dia.) was positioned over the left parietal cortex, oriented normal to the skull.

Recording (anesthetized): In V1, recordings were performed with a ~4x4 mm 96 electrode Utah array, inserted roughly 600µm into cortex (1 mm electrode length, 400 micron spacing). MT recordings were performed with an array of movable electrodes and tetrodes (Thomas Recording), inserted at an angle of 20° from horizontal and positioned roughly 16 mm lateral to the midline and 8 mm posterior to the lunate sulcus. V1 and MT recordings were performed in separate animals. Neuronal responses that exceeded a user-defined voltage threshold were digitized at 30 or 40 kHz. Waveforms were classified using Plexon Offline Sorter into single and multi-units.

Recording (awake): Before each recording session, a guide tube was inserted through the dura mater to gain access to the cortex. Glass or parylene-C-coated tungsten electrodes (FHC) were lowered through the guide tube with an electronic micropositioner (NAN). MT was identified online on the basis of functional criteria (high fraction of direction selective cells with receptive fields that are small compared to the neighboring area MST) and its expected depth relative to the dura mater. Recording locations were confirmed using structural magnetic resonance imaging. Signals were digitized at 25 kHz and stored for offline spike sorting (using KlustaKwik). Eye position was recorded using an Eyelink II infrared video system (500Hz).

Stimulus Presentation (anesthetized): Custom software based on OpenGL (EXPO) was used to generate all stimuli, which were displayed on a calibrated CRT monitor (1024x768 pixels, refresh rate of 100Hz, ~40 cd/m2 mean luminance) placed 80 (MT) or 110 cm (V1) from the animal. In V1, spatial receptive fields (RFs) were estimated using small drifting gratings (0.5 deg diameter, 4 orientations, 1 cycle/deg, drift rate of 6.25 Hz, 250 ms presentation) presented at a range of locations spanning a 3 x 3 deg region of visual space. In MT, we used a similar approach but with 1.3 deg diameter gratings presented in a 20 x 15 deg area. These measurements were used to
center the stimuli over the aggregate spatial receptive field and, when considering responses to small gratings, to select units whose receptive fields were at least 50% covered by the stimulus for further analysis.

Stimulus Presentation and Behavioral Control (awake): We used in-house OpenGL based software (neurostim.sf.net) for behavioral control and stimulus presentation on a Sony Artisan monitor (GDM-520; 150Hz; 1024x768 pixels at 57cm). The animal was rewarded with a drop of juice for fixating a red dot (<0.5 deg) for the duration of a trial. Trials in which fixation was not maintained within an invisible 2 x 2 deg. box were discarded. The receptive field was mapped using automated methods (Krekelberg and Albright, 2005) and used to center the stimulus on the receptive field. We first mapped the direction tuning of the cells with the small and large gratings moving in one of 16 equally spaced directions, presented for 1s. This provided us with the pre-adaptation tuning curve and was used to select the adapter direction.

Paradigms and Visual Stimuli (anesthetized & awake): We measured adaptation effects using full contrast sinusoidal gratings with a spatial frequency of 1 cycle/deg and a drift rate of 6.25 Hz. Gratings were either small (1.3 deg diameter) or large (7.4 deg diameter), with the adapter and test stimuli always matched in size.

In anesthetized animals, we measured direction tuning curves before and after adaptation with 16 equally-spaced directions (22.5 deg increments) in V1, and 12 (30 deg increments) in MT. In the brief (0.4s) adaptation paradigm, control (pre-adaptation) and post-adaptation conditions were interleaved. Pre-adaptation trials consisted of a 0.4 s presentation of a gray screen followed by a test stimulus presented for 0.4 s. Adaptation trials consisted of a 0.4 s presentation of an adapter (one of the stimuli in the test ensemble), followed immediately by a 0.4 s presentation of a test stimulus. Trials were separated by 1.2 s of gray screen to allow recovery (Patterson et al., 2013). In the prolonged adaptation paradigm, we used an adapt-test-top-up design. The initial adaptation interval was 40 s, followed by a sequence of 1 s test stimuli and 5 s top-up adapters. Pre-adaptation test stimuli were separated by 5 s intervals of gray screen presentation to maintain the same temporal structure as in the post-adaptation epochs. Pre-adaptation measurements always preceded post-adaptation.

In the awake animal, pre-adaptation measurements were made first, using gratings in 16 equally-spaced directions (22.5 deg increments). On adaptation trials, the adapter was presented for 4 s, and immediately followed by a 1s test grating whose direction of motion was varied around the preferred direction of the neuron in nine equally spaced steps of 22.5 degrees. We chose this reduced paradigm to maximize useful data collection (given the need to maintain fixation) while still allowing a comparison of pre and post-adaptation tuning curves.

Data Analysis: We analyzed all units that had a pre-adaptation maximum stimulus driven firing rate greater than one standard deviation above the mean spontaneous rate (78% of cells recorded in V1, and 56% in MT). For V1 responses, the F1 component of the response and the mean firing rate were calculated, and the greater of the two was used for further analysis. The spontaneous firing rate (i.e. measured during the presentation of a gray screen) was subtracted from the raw response to provide a measure of evoked activity.

Since there are both direction selective (DS) and orientation selective (OS) neurons in V1, we first quantified tuning for each unit with an orientation selectivity index (OSI) and direction selectivity index (DSI). DSI was calculated as,
where $R_n$ is the response to a stimulus drifting in direction $\theta_n$. OSI was calculated similarly, but with $\theta_{2n}$ replacing $\theta_n$. Neurons whose DSI was greater than its OSI were categorized as DS cells, and OS otherwise. For OS cells, the tuning curve peak closest to the adapter was used, encompassing 180 degrees of stimulus orientation. We did not average across directions that shared the same orientation because we wanted to compare V1 effects with DS units in MT. While both peaks of OS tuning functions were affected by adaptation, there was a slightly stronger effect on the peak closest to the adapter. Thus, while the anesthetized V1 data presented here are the same as those used in Patterson et al., 2013, our use here of only one peak of the tuning curve gave rise to small quantitative differences with that study.

We then fit tuning curves with a von Mises function:

$$r_p = m + ae^{b\cos(\theta - \theta_{pref}) - 1}$$

where $r_p$ is the predicted response, $m$ is the baseline offset, $a$ defines the response amplitude, $b$ determines the tuning width, $\theta_{pref}$ is the location of the peak of the tuning curve, and $\theta$ is the direction of the test stimulus (spanning either 180 or 360 degrees). Fits were determined by maximizing the log likelihood of the data given the model predictions, based on the assumption of Poisson spiking statistics (El-Shamayleh and Movshon 2011). The fit quality was calculated as a normalized log likelihood, where the lower bound (a value of 0) consisted of the likelihood of a model with predicted responses equal to the average response across all conditions, and the upper bound (a value of 1) was calculated by using the data as the model (Stocker and Simoncelli 2006; El-Shamayleh and Movshon 2011). We used the fits to measure changes in peak response, shifts in preferred direction, and changes in bandwidth.

Units were discarded from further analysis based on the following criteria: (1) units with a pre- or post-adaptation fit quality of less than 0.5 (46% of cells in V1, fit quality of remaining cells was 0.80; 51% of cells in anesthetized MT, remaining fit quality 0.77; 65% of cells in awake MT, remaining fit quality 0.89), which indicated poor tuning; (2) units with a bandwidth (width of the tuning curve half way between the minimum and maximum) less than 22.5 deg for V1 (8% of remaining cells) or awake MT (0%) or 30 deg for anesthetized MT (0.5%), because we could not accurately measure the tuning curve of these units with our test ensemble; (3) units whose shift in preference was greater than 1 bandwidth unit (4% of remaining V1 cells; 10% of remaining anesthetized MT cells; 0% of remaining awake MT cells), as such large shifts likely indicate that the pre- and post-adaptation data arose from two different units (Dragoi et al. 2000; Kohn and Movshon 2004). For the awake MT data, we applied these criteria in two distinct ways. First, we applied them to both the pre- and post-adaptation tuning for responses to both small and large gratings. Of 43 MT cells recorded for both sizes, 15 passed the criteria for all conditions. While this resulted in a reduction of the population size, it allowed a within-cell comparison of the tuning properties across multiple conditions. Second, we applied the selection criteria separately to the responses to small and large gratings. This yielded a larger population of cells since it allowed us to include cells whose isolation was lost before we collected data for both size conditions. Using less stringent criteria for the data from awake or anesthetized animals did not change the results in any notable way.
Unless otherwise indicated, error bars reflect 95% confidence intervals based on bootstrap analysis. T-tests were used to determine statistical significance, unless otherwise indicated. Ratios were log-transformed before statistical evaluation.

**Results**

We recorded in V1 and MT of 13 anesthetized monkeys. Neurons in V1 had spatial receptive fields at eccentricities of 2 to 3 degrees, in the lower visual field. The receptive fields in MT had eccentricities ranging from 4 to 8 degrees. The recordings consisted of both well-isolated single units, and small multiunit clusters. We found no difference in adaptation effects for these types of recordings, so we pooled our results (see Wissig and Kohn, 2012 for a detailed comparison). We also recorded from well-isolated single units and small multiunit clusters in area MT of one awake macaque monkey, with receptive fields at eccentricities ranging from 0.5 to 5 degrees.

**Characterization of V1 and MT responses**

We first determined basic response properties of V1 and MT neurons based on the large anesthetized data set, so that we could best compare adaptation effects in the two areas. We measured response latency, defined by the first 10 ms time bin in which the unit fired 1.5 standard deviations above its mean spontaneous rate, when that bin was followed by at least 4 successive bins that exceeded the same threshold. Latency differed only slightly between V1 (median of 70 ms) and MT (median of 80 ms; p=0.08 for comparison with V1), consistent with previous estimates (Schmolesky et al. 1998). For our analysis we therefore used a common response window beginning 50 ms after stimulus onset and extending to its offset, unless otherwise noted.

We next compared the bandwidth of V1 and MT tuning, defined as the width of the tuning curve midway between the maximal and minimal response. V1 neurons (n=418) had narrower tuning (57.2±0.9 deg, s.e.m.) than MT (77.7±3.1 deg, p<0.0001 for comparison, n=98) when measured with large gratings (7.4 degree dia.; Figure 1), consistent with previous work (Albright, 1984). Mean bandwidth was also narrower in V1 (69.6±1.9 deg, p<0.0001 for comparison) than MT (98.4±5.1 deg), when measured with small gratings (1.3 degree dia.). The tuning measured with small gratings was substantially broader than that measured with large gratings, in both V1 (p<0.0001) and MT (p<0.0001). This is presumably a result of the surround suppression recruited by large stimuli, which previous studies have shown can lead to a sharpening of tuning in V1 (Ringach et al. 1997; Chen et al., 2005). Because of differences in bandwidth across areas and stimulus sizes, we normalized all relevant measurements by the bandwidth of each cell to ensure a more fair comparison.

**Effects of prolonged adaptation are similar in V1 and MT**

We have recently shown that the effects of prolonged adaptation in V1 are dependent on stimulus size (Wissig and Kohn, 2012; Patterson et al., 2013). Prolonged adaptation (40 s) with small gratings causes a strong, stimulus-specific suppression of responsivity, resulting in repulsive shifts in preference for neurons whose preference is slightly offset from the adapter; adaptation with large gratings has a weaker effect on responsivity and often causes tuning to shift toward the adapter.
We therefore first determined whether the effects of prolonged adaptation in MT displayed the same dependence on stimulus size as those in V1. Figure 2A compares the peak response ratio (after adaptation compared to before) for V1 (open bars) and MT (filled) units, when measured with small gratings; Figure 2B shows the corresponding data for large gratings. The effects are binned as a function of the neuron’s offset from the adapter, since it is well established that this offset strongly influences the observed effects (Muller et al. 1999; Dragoi et al. 2000; Kohn and Movshon 2004). Neurons within less than 0.2 bandwidth units of the adapter were designated as preferred adapted cells, 0.2-0.5 bandwidth units away as near-flank adapted, 0.5-1 bandwidth units away as far-flank adapted, and those greater than 1 bandwidth unit away as off-flank adapted.

A three factor ANOVA showed that the response ratio depended on stimulus size (F=24.87, p<0.0001), and the neuron’s offset from the adapter (F=17.07, p<0.0001), but was not significantly different in V1 and MT (F=3.30, p=0.07). In both areas, adaptation with small gratings caused a stronger reduction in peak response, with a geometric mean response ratio for preferred-adapted neurons of 0.42 in V1 and 0.33 in MT. There was no difference between effects for preferred-adapted neurons in V1 and MT (p=0.4), or for those at any other offset (p>0.1). For large gratings, the mean response ratio for preferred-adapted neurons in both V1 (0.64; p=0.007) and MT (0.58; p=0.0008) was greater than after adaptation with small gratings, indicating a weaker adaptation effect. There was no difference between effect measured in V1 and MT with large stimuli at any offset (p>0.3).

It is notable that the strongest reduction in both V1 and MT responsivity was observed after adaptation with small stimuli. The small gratings we used are approximately the size of a parafoveal V1 receptive field (Cavanaugh et al. 2002), and thus elicited a robust response in V1 neurons (mean peak firing rate of 31.8±1.9 spikes/s, s.e.m.). Large gratings encroach on the suppressive surround, and thus led to weaker V1 responses (17.8±0.7 spikes/s, p<0.0001 for difference with responses to small gratings). In MT we observed more robust responses to large gratings than small ones (17.8±1.9 vs. 10.9±2.1 spikes/s, p=0.055). This is because the small gratings were much smaller than the typical MT receptive field size at the eccentricity of our recordings (3-7 degrees), whereas the large stimulus filled the MT RF. Thus, small adapters caused a stronger loss of responsivity in MT, despite driving neurons roughly half as well as large gratings.

As for the response ratio, shifts in preference depended on stimulus size (F=6.33, p=0.01) and the neurons’ offset from the adapter (F=12.43, p<0.0001), but we observed no difference between effects in V1 and MT (F=1.19, p=0.3). Adaptation with small gratings caused repulsive shifts in tuning in preferred-adapted neurons in V1 (0.16 bandwidth units) and MT (0.17 bandwidth units, p=0.9 for difference). Effects were weak for near- and far-flank adapted cells with no difference between areas (p>0.4). The preference of off-flank adapted units shifted toward the adapter, both in V1 (-0.07 bandwidth units) and in MT (-0.2 bandwidth units; p=0.02 for comparison with V1).

Whereas the most prominent effect of adapting with small gratings were repulsive shifts in preference, adaptation with large stimuli caused attractive shifts in preference in both areas (Figure 2D). V1 neurons whose preferences fell within 1 bandwidth unit of the adapter (preferred and flank-adapted cells) shifted -0.04 bandwidth units on average (p=0.0009 for difference with 0) and MT neurons shifted -0.05 bandwidth units (p=0.02 for difference with 0). Shifts in preference were significantly more attractive in both V1 (p<0.0001) and MT (p=0.01) for large
compared to small gratings. There was no difference in the average shift in preference between V1 and MT for any offset, when large stimuli were used (p>0.1).

Finally, we observed clear bandwidth narrowing in both V1 and MT for both small and large gratings (Figure 2E, F). Bandwidth narrowing depended on the neurons’ offset from the adapter (F=41.33, p<0.0001), but not on stimulus size (F=1.40, p=0.2, see also Wissig and Kohn 2012; Patterson et al 2013) or cortical area (F=3.63, p=0.06). For large stimuli, however, MT did show a slightly greater bandwidth narrowing for preferred-adapted cells (V1=0.80, MT=0.62, p=0.004), and greater broadening for off-flank adapted cells (V1=1.04, MT=1.18, p=0.005).

In summary, the nature and magnitude of effects induced by prolonged adaptation depended strongly on stimulus size, but not on whether the recordings were in V1 or MT. In both areas, adaptation with small gratings caused a strong response reduction and repulsive shifts in preference for neurons slightly offset from the adapter. Adaptation with large gratings resulted in a weaker response reduction and more attractive shifts in both areas. This similarity occurred despite V1 neurons being driven more strongly by the small stimulus whereas MT neurons were driven more strongly by the large stimulus.

Size-dependent adaptation effects in MT of awake monkeys

Our anesthetized data demonstrate that adaptation effects are strongly modulated by stimulus size. To determine whether effects in awake animals also depend on stimulus size, we measured direction tuning in MT of awake monkeys before and after adaptation. Given the need for maintained fixation during the entire trial, the adaptation duration was limited to 4s. This duration is sufficient in anesthetized animals to reveal the size-dependence of adaptation effects (Patterson et al., 2013). We measured responses from 100 to 400ms after test stimulus onset, to avoid the onset transient, for which adaptation effects are not size-dependent (Patterson et al., 2013).

The direction tuning for one MT neuron is shown in Figure 3, measured with small (Figure 3A) and large (Figure 3B) gratings. Adaptation with small stimuli caused a reduction in peak response (red compared to black) and a weak repulsive shift in preference (0.02 bandwidth units). With large gratings, responsivity increased after adaptation (response ratio of 1.09), although the neuron was driven much more strongly than with small gratings. Tuning also shifted towards the adapter (-0.13 bandwidth units).

A similar size-dependence was apparent in the effects measured in the full population for which we obtained good measurements of tuning before and after adaptation for both stimulus sizes (n=15 neurons passed the tuning selection criteria for both large and small adapters; see Methods). Figures 3C-E compare changes in responsivity, preference, and bandwidth for all cells, for responses to small and large gratings. The filled symbols represent cases when the adapter fell within 1 bandwidth unit of the unit’s preference; open symbols represent cases where the adapter was more offset. Peak responsivity (Figure 3C) was reduced when small stimuli were used (mean ratio of 0.63 across all offsets, p=0.001 for difference with 1), but not when large stimuli were used (0.92, p=0.3). The response ratio was significantly smaller for small stimuli (p=0.02).

Tuning shifted toward the adapter when large stimuli were used (-0.11 bandwidth units; p=0.01 for difference with 0), but not when small stimuli were used (0.02 bandwidth units, p=0.4) and there was a significant difference between the two conditions (Figure 3D; p=0.02). A significant bandwidth narrowing was observed with both small (0.83, p=0.01) and large gratings (0.72, p<0.001), which was similar in magnitude for the two conditions (Figure 3E; p=0.13).
We performed additional analysis using units that met our selection criteria for responses to either small or large gratings. This yielded 21/51 (41%) recorded units for small stimuli, and 28/58 (48%) for large stimuli. The effects in these cells are shown in Figure 4, as a function of the offset of neuronal preference from the adapter; the data from anesthetized animals are re-plotted here (Figure 2) to allow a more direct comparison. We compared effects in these units from awake animals with those measured in MT of anesthetized animals, using a three-way ANOVA with size (small vs. large), state (awake vs. anesthetized), and offset of neuronal preference as factors. For response ratios, this revealed an effect of stimulus size (p=0.002), but not offset (p=0.4) or state (p=0.1). For shifts in preference, there was a significant influence of stimulus size (p=0.01) and offset (p=0.0003) but not state (p=0.7). Bandwidth ratios were not significantly influenced by any factor (p>0.08). Thus, effects were clearly modulated by stimulus size and adapter offset, but there was no significant difference between data from anesthetized and awake MT.

We conclude that the influence of stimulus size on adaptation effects is robust to anesthesia. We note that although the differences between anesthetized and awake data sets did not reach statistical significance, our data do not allow us to determine whether adaptation effects are the same in these two experimental preparations. This is both because of the limited power afforded by our awake data and because of the difference in adaptation duration (4 s in the awake vs. 40 s in the anesthetized).

**FIGURE 4 NEAR HERE**

In summary, we found that adaptation effects in awake monkeys were size-dependent, as they were in anesthetized animals. Adaptation with small gratings caused a significant response reduction, whereas large gratings did not reduce peak responsivity and caused tuning to shift more strongly toward the adapter.

**Adaptation effects in direction selective and orientation selective V1 neurons**

MT receives direct input from direction selective (DS) V1 cells (Shipp and Zeki 1989; Movshon and Newsome 1996). The majority of our sampled units were orientation selective and we wondered whether DS cells in V1 might adapt differently. Previous reports suggest that there is no difference between shifts in tuning preference in DS and OS V1 neurons (Kohn and Movshon 2004), but that study used stimuli which were optimized for each individual unit and did not investigate the size-dependence of the induced effects. To determine whether DS and OS cells adapt similarly, we compared the effects of 40s adaptation with small and large stimuli for these cell types.

**FIGURE 5 NEAR HERE**

We defined DS cells as those which had a direction selectivity index that was greater than the orientation selectivity index (see Methods). By this lax definition, fourteen percent (85/600) of the recorded V1 units were DS (Figure 5). We focused on a subset of units (n=38) whose preference was within 1 bandwidth unit of the adapter because effects were strongest for these neurons. Figure 6A shows the peak response ratios for the DS (top) and OS (bottom) cells, for response to small gratings. There was no significant difference in these ratios between DS cells and OS cells (0.74 for DS vs 0.56 for OS; p=0.07). This was also the case for responses measured with large gratings (Figure 6B; 0.73 for DS, 0.74 for OS, p=0.9). Shifts in preference were repulsive and similar in magnitude for both cell types when small stimuli were used (Figure 6C; DS=0.01, OS=0.05, p=0.3). When large stimuli were used, shifts were attractive and did not
differ significantly between cell classes (Figure 6D; DS=-0.12, OS=-0.03, p=0.053), although DS
cells tended to shift more toward the adapter than OS cells. There was also no difference between
the change in tuning bandwidth for DS and OS cells, for responses to small (Figure 6E; DS=0.76,
OS=0.80, p=0.5) or large gratings (Figure 6F; DS=0.83, OS=0.86, p=0.7).

FIGURE 6 NEAR HERE

Adaptation effects were thus similar for V1 OS and DS cells. This suggests that the cells more
likely to project directly to MT do not adapt differently from the rest of the population.

Effects of brief adaptation are similar in V1 and MT

Brief (0.4 s) adaptation affects primarily the early response epoch, or onset transient, in V1
(Patterson et al., 2013). During this epoch, surround suppression is weak. As a result, the effects
of brief adaptation with large grating stimuli are similar to those seen with small gratings: both
cause a stimulus-specific loss of responsivity, leading to repulsive shifts in preference for neurons
whose preference is slightly offset from the adapter (Patterson et al., 2013). We next sought to
determine whether MT showed a similar behavior to V1 following brief adaptation with large
stimuli.

We first compared response dynamics in V1 and MT, using each neuron’s preferred stimulus.
Figures 7A and 7B show population peristimulus time histograms (PSTH) for V1 and MT,
respectively, for neurons whose preference was within 1 bandwidth unit of the adapter. In both
areas, adaptation reduced responsivity primarily in the initial response epoch (red after adaptation
compared to black before), with little or no effect on the late response epoch. For this reason, we
compared effects on tuning during the first 100ms of the response (50 to 150ms; highlighted in
Figures 7A and B, slightly longer than the 50-100 ms epoch used in Patterson et al., 2013).

FIGURE 7 NEAR HERE

Response ratios were similar in V1 and MT (Figure 7C), with the effects depending on the
preference of the neuron (2 way ANOVA; F=11.46, p<0.0001) but not area (F=0.33, p=0.6).
Response ratios were smallest for preferred-adapted cells (0.44 in V1 and 0.48 in MT). There
was no difference between response ratios for V1 and MT neurons for any offset (p>0.3).
Similarly, shifts in preference were repulsive in both V1 and MT (Figure 7D), and depended on
cell preference (F=5.37, p=0.001) but not area (F=0.89, p=0.3). Preferred, near-flank, and far-
flank neurons showed significant repulsive shifts in V1 (mean=0.11; p<0.0001, difference from
0) and MT (mean=0.06; p=0.03, difference from 0). There was no difference between V1 and MT
at any stimulus offset (p>0.5). Changes in tuning bandwidth changes also depended on the cell’s
preference (Figure 7E; F=4.77, p=0.003) but not area (F=0.48, p=0.5).

In summary, we found that brief adaptation with large gratings had similar effects in V1 and MT.
In both areas, adaptation affected primarily the initial response epoch, and led to a strong loss of
responsivity and repulsive shifts in preference. This is in contrast to the effects of prolonged
adaptation with large gratings, which led to a weaker loss of responsivity and attractive shifts in
both areas (Figure 2). This is because prolonged, but not brief, adaptation weakens surround
suppression. Thus, effects of adaptation are similar in V1 and MT, for responses measured with
small and large gratings and after brief or prolonged adaptation.
**Discussion**

We found that the effects of adaptation depended strongly on stimulus size and adaptation duration, but were similar in V1 and MT. In both V1 and MT, prolonged adaptation with small and large stimuli generated opposite shifts in preference and different degrees of response reduction. In both areas, brief adaptation with large stimuli resulted in strong response reduction and repulsive shifts in preference. Our findings strongly indicate that previously reported disparities between adaptation effects in V1 (Muller et al. 1999; Dragoi et al. 2000; Dragoi et al. 2002) and MT (Kohn and Movshon 2004) are the result of differences in stimulus size (Wissig and Kohn 2012; Patterson et al., 2013), and do not reflect a fundamental difference in how these networks adjust to recent stimulus history. Previous V1 and MT studies used stimuli tailored to the receptive field properties of neurons in each area. Because of the larger spatial receptive fields of MT neurons, larger stimuli were used there, giving rise to the difference with effects previously reported in V1.

While adaptation effects were not noticeably different between V1 and MT, we cannot exclude the possibility that there is some quantitative difference that would only be apparent with a larger sample of neurons. However, our sample size and statistical power was sufficient to reveal a strong influence of adaptation duration and stimulus size. Thus, if there are differences in adaptation effects between V1 and MT they are substantially weaker than the influence of these other factors. We note also that our finding of similar effects in V1 and MT apply to our stimulus ensemble but do not imply that effects in these two areas need always be similar.

Several comparisons did reveal effects that were slightly different in the two areas. For instance, following prolonged adaptation with small stimuli, off-flank adapted cells shifted more strongly toward the adapter in MT. This difference might be explained by motion opponency in MT, an inhibitory input provided by cells with the opposite direction preference (Snowden et al. 1991). If off-flank adapted MT neurons received weaker inhibition from cells with the near-opposite preference (since these would be preferred-adapted and thus their responsivity strongly reduced), this could cause disinhibition leading to attractive shifts. One might expect this effect to be particularly strong for small stimuli for which adaptation causes a stronger response reduction. This could also explain why we observed no shift on average, rather than repulsive shifts, in the awake MT data when small stimuli were used: for a substantial proportion of these neurons, the adapter was far from the preferred direction.

In addition, we found that prolonged adaptation effects in MT of awake monkeys also depend on stimulus size. This is consistent with the size-dependence of perceptual aftereffects, measured in human studies. For instance, the motion aftereffect induced by small adapters is stronger than that induced by large ones (Murakami and Shimojo 1995; Sachtler and Zaidi 1993; Tadin et al. 2003). Similarly, the perceptual effects of an adapter of a fixed size increase with eccentricity, perhaps because of weaker surround effects in larger, peripheral receptive fields (Johnston and Wright 1983; Murakami and Shimojo 1995; Tadin et al. 2003; see also Wissig et al., 2012). Although our awake data revealed a robust size-modulation of adaptation effects, they did not allow us to establish that effects were the same in the two experimental preparations. Our sample size was insufficient for this purpose and the adaptation duration, which can strongly influence effects (Figure 7; Patterson et al., 2013), also differed between the anesthetized and awake experiments. However, previous work that affords a more straightforward comparison of adaptation effects in awake and anesthetized animals failed to find notable differences either in V1 (Muller et al. 1999; Dragoi et al. 2000; compared to Dragoi et al. 2002) or MT (Priebe et al. 2002).
To our knowledge, our study is the first to use the same stimulus ensemble to compare how adaptation alters tuning at successive stages of visual processing. Several previous studies, however, have compared adaptation effects on responsivity and contrast or coherence sensitivity across stages of the visual system. For instance, studies of V1 contrast adaptation failed to find changes in the LGN under similar stimulus conditions (Movshon and Lennie, 1979; Ohzawa et al., 1985). Nelson (1991a) studied the time course of suppression induced in V1 by the brief presentation of a bar stimulus; a similar approach revealed some suppressive effects in the LGN but these could not fully explain those in V1 (Nelson, 1991b). McLelland et al. studied responses to afterimages induced by prolonged presentation of static images, and found these decayed much more quickly in cortex (McLelland et al., 2010) than in the LGN (McLelland et al., 2009). Nelson (1991a) studied the time course of suppression induced in V1 by the brief presentation of a bar stimulus; a similar approach revealed some suppressive effects in the LGN but these could not fully explain those in V1 (Nelson, 1991b). McLelland et al. studied responses to afterimages induced by prolonged presentation of static images, and found these decayed much more quickly in cortex (McLelland et al., 2010) than in the LGN (McLelland et al., 2009). Crowder et al. (2006) report similar effects of contrast adaptation in V1 and V2 of cat visual cortex. Finally, Priebe et al. (2002) showed that the spatial specificity of adaptation-induced changes MT responsivity could not be explained by effects in V1. However, several of these studies tailored stimuli to each neuron. This complicates the interpretation, as any similarity or difference between areas can reflect the preferences of neurons there (leading to systematic differences in the stimuli used) rather than how the areas adjust to a particular input. Perhaps more importantly, these previous studies did not explore how adaptation altered tuning, our focus here.

Previous work suggests that the effects of prolonged adaptation with drifting gratings in MT are inherited from early visual areas (Kohn and Movshon, 2003): adapting a portion of an MT neuron’s spatial receptive field with a small stimulus results in a strong change in contrast sensitivity at that location, but not at other locations within the receptive field. Such spatial specificity suggests that effects are induced where receptive fields are smaller than in MT, such as V1, and these are then inherited by MT. Our finding that adaptation with small gratings caused a greater loss of MT responsivity than adaptation with large gratings is consistent with MT effects being inherited from early visual cortex. V1 responses were substantially stronger to small gratings than to large ones, and adaptation with small gratings resulted in a stronger loss of V1 responsivity. This is because large gratings recruit surround suppression; adaptation weakens the influence of the surround, leading to a disinhibition that partially offsets the adaptation-induced loss of responsivity within the receptive field. In MT, small gratings provided substantially weaker drive than large gratings, because the larger stimulus was not sufficiently big to recruit strong surround suppression in MT. Despite evoking weaker responses in MT, small gratings caused a stronger loss of responsivity, as they did in V1. This can be attributed to effects originating in V1, or elsewhere in the early visual system.

It is important to note that the similar way in which V1 and MT tuning preferences are altered, for stimuli of different sizes and adapters of different durations, is not by itself strong evidence that MT effects are inherited from V1. First, the similarity we observed was evident when effects were measured relative to pre-adaptation tuning bandwidth; in absolute terms, the shifts in MT preference were thus roughly 50% larger than in V1. Second, previous work has shown that altering feedforward input to a recurrent network can give rise to distinct tuning effects there (Kohn and Movshon, 2004; Compte et al., 2006). In a network with strong recurrent connections, the tuning of an individual neuron can reflect dynamic interactions among neurons with different tuning properties. These interactions can manifest themselves in many different ways, for instance, as motion opponency or spatial inhomogeneities within the receptive field (Richert et al., 2013). If one subpopulation of neurons within such a recurrent network receives weakened feedforward input, these interactions are changed. This can result, for instance, in reduced lateral inhibition to neighboring neurons, causing their tuning to shift toward the adapter. Thus, the similar effects of our adapting stimulus ensemble on the tuning of V1 and MT neurons do not follow directly from the suggestion that MT passively inherits effects from V1. Rather, it suggests...
a common active strategy for adjusting to recent sensory drive in these two networks, perhaps
implemented through distinct circuit mechanisms.

Our explanation for the size dependence of adaptation effects is that the surround is weakened
after prolonged stimulation (Wissig and Kohn, 2012; Patterson et al., 2013). Previous modeling
work by Teich and Qian (2003) showed that changes in the relative strength of recurrent
excitatory and inhibitory connections can generate opposite shifts in neuronal preferences and a
range of effects on responsivity. Our explanation is in no way inconsistent with this model. Our
explanation provides insight into the plasticity triggered by stimuli of different size and duration,
but does specify how this occurs; the Teich and Qian model is specific about the mechanisms
underlying changes in tuning, but does not explain under what stimulus conditions these are
likely to be recruited. It is tempting to relate these—for instance, by equating a weakened
surround with weaker inhibition—but this is simplistic and likely incorrect. The mechanisms of
surround suppression remain poorly understood (Angelucci and Bressloff, 2006) and recent work
has provided inconsistent answers as to its relationship to inhibitory input (Ozeki et al., 2009;
Haider et al., 2010).

While our primary focus is to understand how the visual system adapts to its environment, our
findings have important implications for fMRI studies that use adaptation as a tool to infer
selectivity. In such studies, feature selectivity is inferred from the reduced BOLD response that
follows the repeated presentation of two identical stimuli compared to the response that follows
the presentation of two stimuli that differ along some feature dimension (Krekelberg et al., 2006).
Our finding that large stimuli cause less response reduction than small stimuli (Figure 2A and 2B)
show that this inference is only valid if one takes into account the size of the stimulus compared
to the typical receptive field size in the area of interest. With this knowledge the finding that
fMRI adaptation increases along the visual hierarchy is easily understood as the result of an
increase in RF size, rather than a counterintuitive increase in orientation selectivity, or a true
change in adaptability (see Wissig et al., 2012 for further discussion). Our findings may also
explain why some high-level feature changes (e.g. Faces vs. Houses) result in selective fMRI
adaptation in high level areas such as the FFA but not in V1, even though pictures of faces likely
differ from pictures of houses in local orientation content (Krekelberg et al, 2006). Future fMRI
adaptation studies should therefore take average receptive field size into account or vary image
size, especially when comparing selectivity across areas.
Figure 1: Characteristics of V1 and MT neuronal responses. Histograms of the tuning bandwidths for the V1 (top, white) and MT (bottom, gray) units. Arrowheads indicate mean bandwidth.

Figure 2: Comparison of the effects of prolonged adaptation effects in V1 and MT, for small and large gratings. V1 data are shown in white and MT in gray. (A,B) Peak response ratio, plotted as a function of the units’ preference relative to the adapter (in bandwidth units), for responses to small (A) and large (B) gratings. (C,D) Shifts in preference plotted as a function of preference for small (C) and large (D) gratings. (E,F) Bandwidth ratio, as a function of preference for small (E) and large (F) gratings. Error bars indicate 95% CI.

Figure 3: Adaptation effects in MT of awake macaque monkeys. (A, B) Direction tuning of an example MT unit before (black) and after (red) 4 s adaptation with small (A) or large (B) gratings. Data points are mean measured responses; error bars indicate s.e.m. Solid lines are von Mises fits to the data. Arrowhead indicates the direction of the adapter. (C) A comparison of the peak response ratio for responses to small and large gratings. Each symbol represents data from an individual MT unit. Red circles indicate mean values. Filled black circles indicate cells whose preference was within 1 bandwidth unit of the adapter. (D) Same for shifts in preference. (E) Same for bandwidth ratio.

Figure 4: Comparison of adaptation effects in MT of awake and anesthetized monkeys, as a function of offset of neuronal preference from the adapter. (A) Comparison of response ratios in awake (left) and anesthetized (right) monkeys, for offsets of 0-1, >1, and all offsets. Dark bars indicate responses with small gratings; light bars data for large gratings. (B) Shift in neuronal preferences, following the conventions of (A).

Figure 5: Direction and orientation selectivity in V1 neurons. Orientation selectivity index (OSI) is plotted against the direction selectivity index (DSI), for small (left) and large (right) gratings. Each symbol represents data from a unit. We defined as direction selective those units falling above the diagonal (DSI>OSI).

Figure 6: Comparison of prolonged adaptation (40 s) effects for V1 direction selective (DS) and orientation selective (OS) units whose preference was within 1 bandwidth unit of the adapter. (A,B) The peak response ratio measured with (A) small and (B) large gratings. Data from DS units are shown on top and from OS units on bottom. Arrowheads indicate mean. (C,D) Shifts in preference for responses measured with small (C) and large (D) gratings. (E,F) The bandwidth ratio measured with small (E) and large (F) gratings.

Figure 7: Comparison of brief adaptation effects in V1 and MT for large stimuli. (A,B) Peristimulus time histogram (PSTH) for the preferred stimulus, for all units whose preference was within one bandwidth of the adapter. Data before adaptation are shown in black, and after adaptation in red, for units in V1 (A) and MT (B). Gray highlighted area indicates the time window used to measure tuning. Shading indicates s.e.m. We normalized the PSTH for each neuron by its peak amplitude and then averaged across units. (C) Peak response ratios, as a function of units’ offset from adapter in bandwidth units, for V1 (white) and MT units (gray). (D) Shifts in preference for V1 (white) and MT units (gray). (E) Bandwidth ratios for V1 (white) and MT units (gray). Error bars indicate 95% CI.
References


Patterson et al. - Fig 1
Offset from adapter (bandwidth units)

Patterson et al. - Fig 2
Firing rate (spikes/s)

Direction of test stimulus (deg)

Patterson et al. - Fig 3
Direction selectivity index (DSI)

Orientation selectivity index (OSI)

Patterson et al. - Fig 5
Patterson et al. - Fig 7