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Orientation-Tuned fMRI Adaptation in Human Visual Cortex

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Fang, Fang, Scott O. Murray, Daniel Kersten, and Sheng He. Orientation-tuned fMRI adaptation in human visual cortex. *J Neurophysiol* 94: 4188–4195, 2005. First published August 24, 2005; doi:10.1152/jn.00378.2005. Adaptation is a general property of almost all neural systems and has been a longstanding tool of psychophysics because of its power to isolate and temporarily reduce the contribution of specific neural populations. Recently, adaptation designs have been extensively applied in functional MRI (fMRI) studies to infer neural selectivity in specific cortical areas. However, there has been considerable variability in the duration of adaptation used in these experiments. In particular, although long-term adaptation has been solidly established in psychophysical and neurophysiological studies, it has been incorporated into few fMRI studies. Furthermore, there has been little validation of fMRI adaptation using stimulus dimensions with well-known adaptive properties (e.g., orientation) and in better understood regions of cortex (e.g., primary visual cortex, V1). We used an event-related fMRI experiment to study long-term orientation adaptation in the human visual cortex. After long-term adaptation to an oriented pattern, the fMRI response in V1, V2, V3/VP, V3A, and V4 to a test stimulus was proportional to the angular difference between the adapting and test stimuli. However, only V3A and V4 showed this response pattern with short-term adaptation. In a separate experiment, we measured behavioral contrast detection thresholds after adaptation and found that the fMRI signal in V1 closely matched the psychophysically derived contrast detection thresholds. Similar to the fMRI results, adaptation induced threshold changes strongly depended on the duration of adaptation. In addition to supporting the existence of adaptable orientation-tuned neurons in human visual cortex, our results show the importance of considering timing parameters in fMRI adaptation experiments.

INTRODUCTION

Adaptation—the sensitivity adjustment in response to a stimulus—is a fundamental property of nearly every nervous system and has also served as a powerful behavioral tool for showing selective neural sensitivities to various stimulus dimensions. For example, both the tilt-aftereffect and elevated contrast detection thresholds after prolonged exposure to an oriented grating provide compelling behavioral evidence of orientation-tuned neurons (Blakemore and Nachmias 1971; Gibson and Radner 1937). More recently, the use of adaptation as an experimental tool has been combined with functional MRI (fMRI) to make inferences about neural sensitivities in specific cortical regions (e.g., Engel 2005; Engel and Furmansi 2001; Grill-Spector and Malach 2001; Grill-Spector et al. 1999; He et al. 1998; Kourtzi and Kanwisher 2000, 2001; Murray and Wojciulik 2004; Tootell et al. 1998b). In a typical fMRI adaptation experiment, an initial stimulus is presented that is presumed to adapt the population of neurons sensitive to that stimulus. After removal of the adapting stimulus, a second stimulus is presented that is either identical to the adapter or transformed in some dimension (e.g., orientation). If the fMRI signal is larger for the transformed stimulus as compared with the identical stimulus, it is inferred that neurons in the region have selective sensitivity to that manipulated dimension because the transformed stimulus is thought to be accessing a separate, unadapted neural population.

The use of fMRI adaptation has been particularly prevalent in object recognition studies of temporal cortical visual areas. In addition, unlike traditional psychophysical adaptation experiments, fMRI adaptation experiments have often used brief (e.g., 300 ms) presentation times (but see also Engel 2005; Engel and Furmanski 2001; He et al. 1998; Tootell et al. 1998b; where tens of seconds adaptation was used). Although the pattern of results in these studies is often consistent with the adaptation logic, there has been little validation of the technique using *1*) stimulus dimensions with well-known adaptive properties (e.g., orientation), *2*) better understood regions of cortex (e.g., V1), and *3*) timing parameters similar to psychophysical studies.

Recently, Boynton and Finney (2003) directly examined rapid adaptation in retinotopic cortex using brief, successive presentations of oriented gratings. They showed a larger signal for orthogonal- than same-orientation stimulus pairs in extrastriate areas, consistent with neural adaptation to orientation, but did not observe any differences in V1. Their result was surprising given the substantial evidence that V1 neurons are sensitive to stimulus orientation (Hubel and Wiesel 1962, 1968) and the neurophysiological evidence of both long-term (Carandini et al. 1998; Movshon and Lennie 1979; Sclar et al. 1989;) and short-term (Muller et al. 1999) pattern-specific adaptation in V1. One possible explanation—with important implications for the use of fMRI adaptation—is that adaptation may operate on different time scales in different cortical areas. For example, obtaining an adaptation signal measurable with fMRI in V1 may require timing parameters that are more similar to traditional psychophysical experiments of adaptation.

In this study, we adopted the paradigm of long-term adaptation that is widely used in psychophysical and neurophysiological studies. We found that in V1 and extrastriate areas, the fMRI signal evoked by the test stimulus had a magnitude proportional to the angular difference between the adapting and test stimuli. Furthermore, the fMRI signal magnitudes in V1 closely followed psychophysically derived contrast sensitivi-

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ties for detecting the test stimulus following adaptation. We also failed to find orientation-tuned fMRI adaptation in V1 with a short-term adaptation paradigm, which replicated Boynton and Finney's (2003) finding and ruled out other potential explanations (e.g., transient attention and apparent motion) of the long-term fMRI adaptation effect.

METHODS

Subjects

A total of five healthy subjects (2 female, 3 male; YJ, WL, PT, FF, and SM) were involved in these experiments. YJ, WL, FF, and SM participated in the long-term psychophysical and fMRI adaptation experiments. YJ, WL, FF, and PT participated in the short-term psychophysical and fMRI adaptation experiments. All were right-handed and ranged in age from 25 to 33 yr. They had normal or corrected-to-normal vision and gave written, informed consent in accordance with procedures and protocols approved by the human subjects review committee of the University of Minnesota.

fMRI experiments

The adapting and test stimuli consisted of 16 100% contrast Gabor patches arranged in two concentric annuli, with mean radii of 2.1 and 4.5° (Fig. 1). Each of the eight patches in the inner annulus had a diameter of 1.9° (σ = 0.38°) and a spatial frequency of 3.7 cycles/°. The eight outer annulus patches each had a diameter of 2.8° (σ = 0.70°) and a spatial frequency of 2.5 cycles/°. The orientation of each Gabor patch in the adapting stimuli was randomized, and the adapting stimuli were fixed in each adaptation scan. Four test stimuli were generated by rotating the individual Gabor patches in the adapting stimulus by ±0, ±7.5, ±30, or ±90°. The rotation direction of each Gabor patch was randomly determined to be either clockwise or counterclockwise.

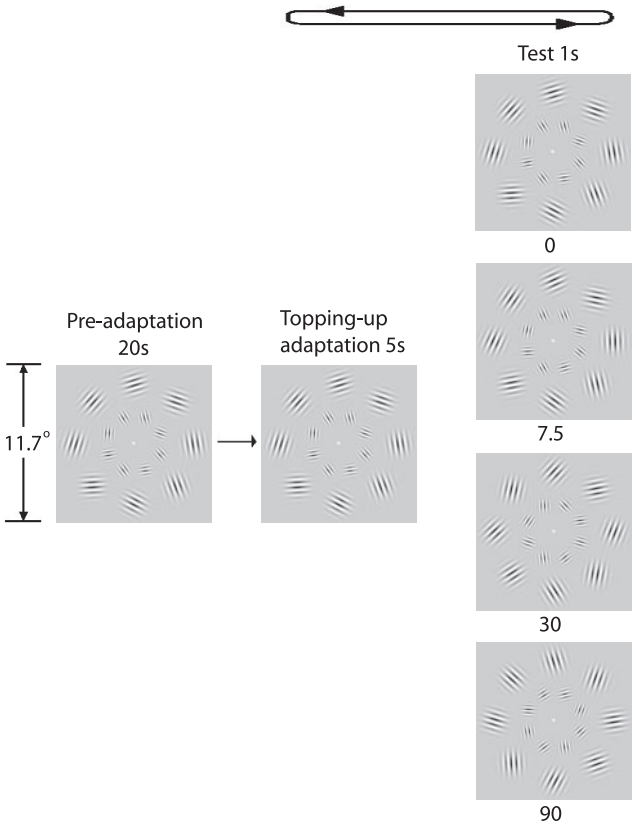

FIG. 1. Schematic of the event-related design in the functional MRI (fMRI) long-term adaptation experiment. With 20 s of preadaptation at the beginning of each scan, 1 of 4 test stimuli (0, 7.5, 30, and 90°) was presented for 1 s after 5-s "topping-up" adaptation. Subjects' attention was directed to a demanding central fixation task.

For the long-term adaptation experiment (Fig. 1), each adaptation scan (total of 8) consisted of 64 continuous trials and began with 20 s of preadaptation. In each trial, after 5-s "topping-up" adaptation, one of four test stimuli was presented for 1 s. During adaptation and test, the Gabor patches were counterphase flickered at 1 Hz. The observers performed a very demanding fixation task in which they needed to press one of two buttons to indicate the luminance change (increase or decrease) of the fixation point (0.2 × 0.2°) as soon as possible. The luminance changes occurred randomly and on average every 1.4 s and lasted 200 ms. In total there were 64 × 8 trials, 128 for each type of test stimuli. The order of the four test stimulus types was counterbalanced across eight adaptation scans using M-sequences (Buracas and Boynton 2002). These are pseudo-random sequences that have the advantage of being perfectly counterbalanced n-trials back (we tested ≤10 trials back), so that trials from each kind of test stimulus were preceded equally often by trials for each of the other kinds of stimuli. For the short-term adaptation experiment (Fig. 4*A*), the adapting stimulus was presented for only 1 s, immediately followed by 1-s test and 2-s blank intervals. All other parameters were the same as the long-term adaptation experiment, except that there was no 20-s preadaptation in the short-term adaptation experiment.

To define retinotopic visual areas, subjects viewed two types of retinotopic mapping stimuli (Engel et al. 1997; Sereno et al. 1995). The first were counterphase flickered (10 Hz) checkerboard wedges of 7° radius located at the horizontal and vertical meridians. These served to map boundaries between visual areas. The second were foveal (2°) and peripheral (9°) counterphase (10 Hz) annuli that served to map the retinotopic extent of each area. Two retinotopic mapping scans were performed—one that alternated the horizontal and vertical meridian stimuli and one that alternated the foveal and peripheral ring stimuli. In both scans, stimuli were presented in 20-s blocks with 10 alternations between conditions. Regions of interest (ROIs) within each retinotopic area were defined by having subjects view a central disk (radius 1.2°) and an annulus (between 1.2 and 5.9° from fixation) with checks that were counterphase flickered (10 Hz) and spatially mutually exclusive. The annuli covered the same area occupied by the 16 Gabor patches used in the adaptation experiment. Stimuli were presented in 20-s blocks with five alternations between conditions.

Psychophysical experiments

Psychophysical contrast adaptation experiments were performed outside the scanner under adaptation conditions designed to match those in the fMRI experiments. Two adapting Gabor patches (diameter: 2.8°; spatial frequency: 2.5 cycles/°; mean radii: 4.5°; σ: 0.70°; 1-Hz counterphase flickering), which were the same as those in the outer annulus in the fMRI experiments, were presented on opposite sides of the fixation point. Like the long-term fMRI adaptation experiments, 20 s of preadaptation was also used. Then, after 5-s "topping-up" adaptation and a 0.5-s blank gap, a low-contrast, 1.5-cycle Gabor patch whose center and spatial frequency were identical to the adapting stimuli was presented for 200 ms on either the left or right side. A 250-ms auditory beep preceding each test stimulus by 250 ms alerted the subject to the ensuing presentation of the test stimulus. Subjects were asked to press a button to make a two-alternative forced-choice (2-AFC) to indicate the location of the test stimulus (left or right of fixation, Fig. 2). Contrast thresholds of test stimuli (82% correct rate to judge their location) after adaptation were estimated by Quest staircases (Watson and Pelli 1983), four times for each subject and test stimulus type. Each staircase consisted of 50 trials, with fixed orientations of adapting and test Gabor patches that

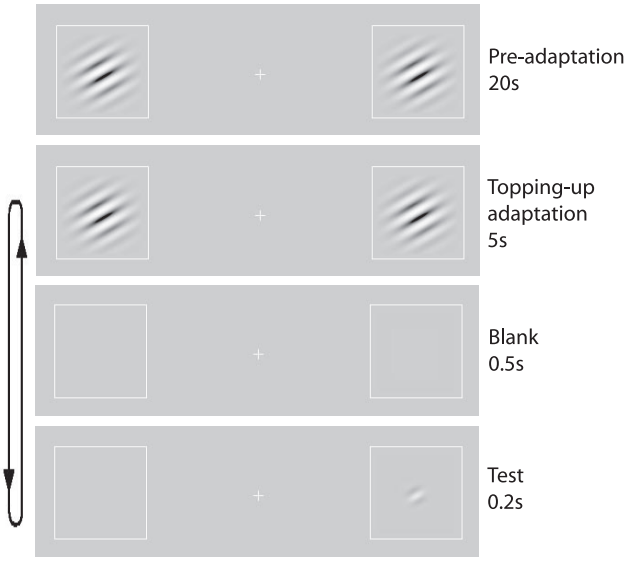

FIG. 2. Schematic of the psychophysical experiment for measuring contrast detection thresholds after long-term adaptation. Twenty seconds of preadaptation was used at the beginning of each staircase. A low-contrast Gabor patch as test stimulus was presented either to the left or right of the fixation point for 0.2 s after 5-s "topping-up" adaptation and a 0.5-s blank gap. Subjects were asked to make a 2-alternative-forced-choice (2-AFC) to indicate the location of the test stimulus.

were randomized at the beginning of the staircase. We also performed a psychophysical short-term contrast adaptation experiment. Parallel to the fMRI experiments, adaptation time was shortened to 1 s, and all other parameters were equivalent to the long-term experiment, except that there was no 20-s preadaptation in the short-term adaptation experiment. The stimuli were presented on a SONY Trinitron Multiscan G420 19-in monitor, with a spatial resolution of 1280 × 1024 and refresh rate of 100 Hz. The viewing distance was 57 cm. The background luminance was 43 cd/m^2, and luminance level in the monitor ranged from 0 to 86 cd/m^2 .

fMRI data acquisition

In the scanner, the stimuli were back-projected using a video projector (60 Hz) onto a translucent screen placed inside the scanner bore. Subjects viewed the stimuli through a mirror located above their eyes. fMRI data were collected using a 3-T Siemens Trio scanner with a high-resolution eight-channel head array coil. Blood oxygen level-dependent (BOLD) signals were measured with an echo-planar imaging (EPI) sequence (TE: 30 ms, TR: 1,000 ms, FOV: 22 × 22 cm^2, matrix: 64 × 64, flip angle: 60, slice thickness: 5 mm, number of slices: 14, slice orientation: axial). The bottom slice was positioned at the bottom the temporal lobes. T2-weighted structural images at the same slice locations and a high-resolution three-dimensional (3-D) structural data set (3D MPRAGE; 1 × 1 ×1-mm^3 resolution) were collected in the same session before the functional runs. The scans for retinotopic mapping were run in a different session in the same scanner.

fMRI data analysis

The anatomical volumes were transformed into a brain space that was common for all subjects (Talairach and Tournoux 1988) and inflated using BrainVoyager 2000. Functional volumes for each subject were preprocessed, which included 3-D motion correction using SPM99, slice scan time correction, linear trend removal, and high-pass (0.015 Hz) (Smith et al. 1999) filtering using BrainVoyager 2000. Correlation analysis was performed on the localizer data to define the ROIs ($r > 0.4$) that had higher BOLD signals for the annulus than the central disk. The first 10 s of BOLD signals were discarded to minimize transient magnetic saturation effects. For the scans with the Gabor adapting and test stimuli, the original BOLD signals from the ROI were transformed into percent signal changes, and event-related was averaged according to the type of test stimuli. Finally, the averaged BOLD signals were baseline-corrected to the time-point at which the test stimuli occurred.

In the long-term adaptation experiment, the peak values of the evoked BOLD signals were defined as the positive peak response for the 30 and 90° test stimuli and the negative peak response for the 0 and 7.5° test stimuli, respectively (Fig. 5*A*). In the short-term adaptation experiment, the univariate BOLD amplitude was computed for each type of test stimulus by averaging the evoked BOLD signal over a 3- to 7-s latency window (Fig. 5*B*) (Ress and Heeger 2003). The window was chosen to bracket the peak response determined from other rapid event-related fMRI experiments (hemodynamic reference scans) conducted in our laboratory for each subject. To compare the fMRI adaptation effect between the long-term and short-term adaptation experiments, we subtracted the BOLD signal evoked by the 0° test stimulus as baseline from those by 7.5, 30, and 90° test stimuli (Fig. 4*B*).

RESULTS

Behavioral responses to fixation tasks

In both short-term and long-term fMRI adaptation experiments, we categorized reaction time (RT) and correct rate (CR) for the fixation task into five groups (test 0, test 7.5, test 30, test 90, and adaptation), dependent on whether there was temporal overlap between the luminance change of fixation and a test stimulus. For example, if subjects made a response to a fixation luminance change, which temporally overlapped with a 7.5° test stimulus, this response was categorized as belonging to the test 7.5 group. If the fixation luminance change didn't overlap with any test stimulus, the response was categorized as belonging to the adaptation group. The temporal variations of subjects' responses were very small, and there was no significant behavioral difference between any pair of groups in both short-term (test 0: 501 ± 27 ms, 0.81 ± 0.02; test 7.5: 490 ± 34 ms, 0.79 ± 0.02; test 30: 495 ± 33 ms, 0.79 ± 0.06; test 90: 501 ± 14 ms, 0.77 ± 0.04; adaptation: 505 ± 18 ms, 0.81 ± 0.03) and long-term (test 0: 501 ± 25 ms, 0.79 ± 0.03; test 7.5: 491 ± 28 ms, 0.81 ± 0.03; test 30: 501 ± 32 ms, 0.81 ± 0.02; test 90: 495 ± 15 ms, 0.80 ± 0.04; adaptation: 523 ± 23 ms, 0.80 ± 0.03) adaptation experiments. This result suggests that subjects' general attentional state did not differ across the different test conditions.

fMRI results

Figure 3*B* shows a time-course of BOLD signal in V1 from a long-term adaptation scan. Figure 3*C* shows event-related averages in V1 evoked by the four test stimuli (0, 7.5, 30, and 90° angular difference from the adaptor) averaged across four subjects. Test stimuli were presented at *time 0*. The fMRI signals show a monotonic increase from 0 to 90° test conditions. This response pattern was consistently observed in all four subjects. A one-way ANOVA shows a significant main effect of the test-adapt angular difference in V1 [$F(3,15) = 28.252$, $P < 0.001$]. It is interesting to note that only the 30 and 90° test stimuli elicited a significant positive peak at a latency of 4 s. The BOLD signals evoked by the 0 and 7.5° test stimuli

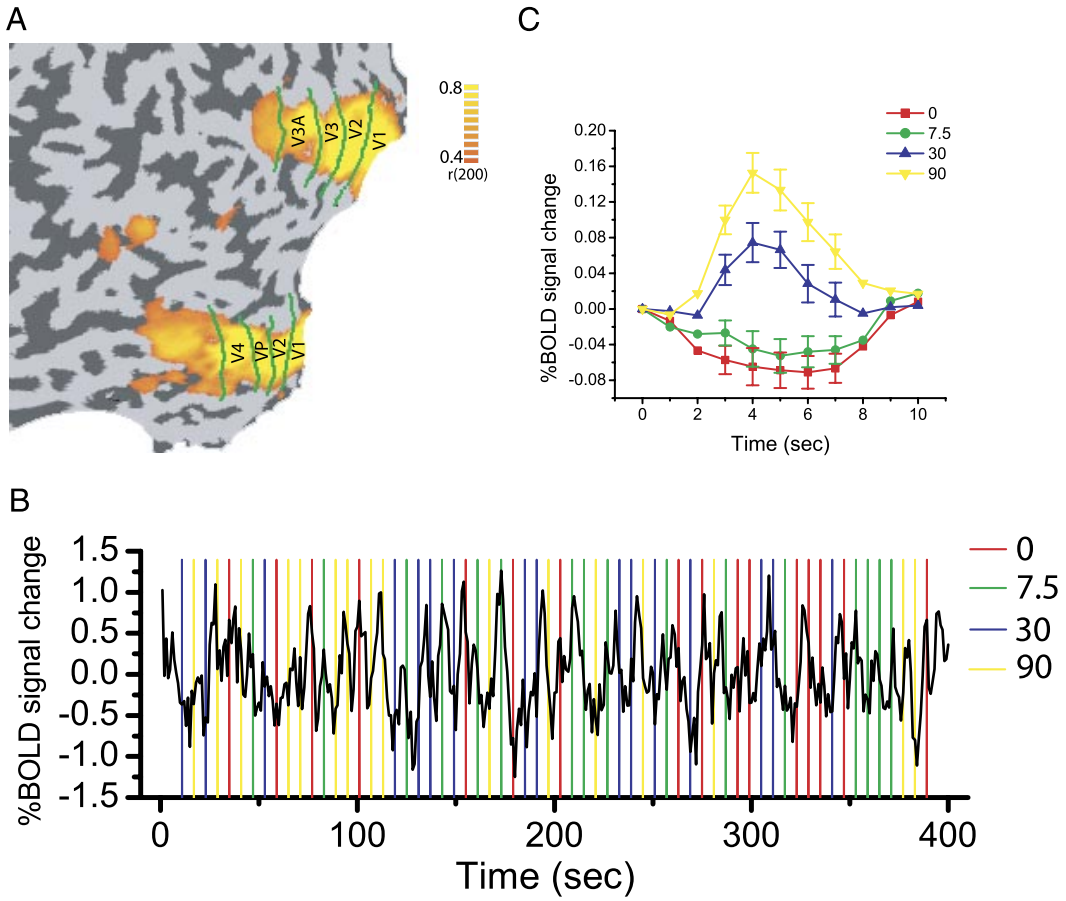

FIG. 3. *A*: region of interest (ROI) depicted on a flattened brain. Green lines are boarders of early visual areas obtained from retinotopic mapping. *B*: example of a blood oxygen level-dependent (BOLD) signal time-course in V1 from a long-term adaptation scan. Colored vertical bars indicate the time-point at which test stimuli were presented. Adapting stimulus was present at all other times. *C*: event-related averages in V1 across 4 subjects representing the fMRI responses to the 0, 7.5, 30, and 90° test stimuli in the long-term adaptation experiment. Error bars denote ±SE across 4 subjects.

are negative and kept decreasing until time-points 5 and 6. This may be attributed to the overlapping neural populations tuned to 0 and 7.5°. The fMRI signals evoked by the 0 and 7.5° test stimuli began to increase after time-point 6 because of the presentation of the next test stimulus.

We also examined the evoked BOLD signals in extrastriate areas (V2, V3/VP, V3A, and V4). As shown in Fig. 5*A*, extrastriate areas also consistently exhibited a monotonic increase in signal from the 0 to 90° test conditions, which was confirmed by ANOVAs [V2: $F(3,15) = 29.768$, $P < 0.001$; V3/VP: $F(3,15) = 31.494$, $P < 0.001$; V3A: $F(3,15) = 52.41$, $P < 0.001$; V4: $F(3,15) = 81.681$, $P < 0.001$]. Also, there was a progressive increase in the magnitude of the adaptation effect through the hierarchy of visual retinotopic areas from V1 to V4.

Figures 4*B* and 5*B* show the results from the short-term adaptation experiment. To compare the fMRI adaptation effect between the long-term and short-term adaptation experiments, the BOLD signal evoked by the 0° test stimulus served as baseline and was subtracted from those evoked by the 7.5, 30, and 90° test stimuli (Fig. 4*B*). The BOLD signals from the short-term adaptation experiment in V1, unlike the long-term one, did not show a monotonic increase from 0 to 90° test conditions, which indicates no (or very weak) short-term adaptation effects in V1. However, as shown in Fig. 5*B*, extrastriate areas gradually exhibited an adaptation effect, and the main ANOVA effect of angular difference reached significance in V3A and V4 [V1: $F(3,15) = 0.557$, $P = 0.653$; V2: $F(3,15) = 2.112$, $P = 0.152$; V3/VP: $F(3,15) = 2.673$, $P = 0.095$; V3A: $F(3,15) = 5.976$, $P = 0.01$; V4: $F(3,15) = 6.859$, $P = 0.006$].

Psychophysical results

The elevation of contrast detection thresholds after adaptation as a function of the angular difference between adapting and test orientations has been widely used to show orientation-selective adaptation in the visual system. Here, we measured the minimum Michelson contrast required to detect the presence of a Gabor patch at the adapted location after 5-s "topping-up" adaptation and 1-s short-term adaptation.

For the long-term adaptation experiment, the psychophysical results (Fig. 6*A*, square) clearly show that visual system is well adapted, and the contrast threshold is proportional to the angular difference between adapting and test orientations. However, in the short-term adaptation experiment, the magnitude of contrast threshold elevation (Fig. 6*B*, circle) is much weaker than that in the long-term one. To compare the psychophysical and fMRI results after long-term adaptation, we plotted the contrast detection threshold against peak fMRI signal values in V1 for each subject (Fig. 6*B*). Linear functions provided a good fit of the data (S1: $y = 0.11007 - 0.29666x$,

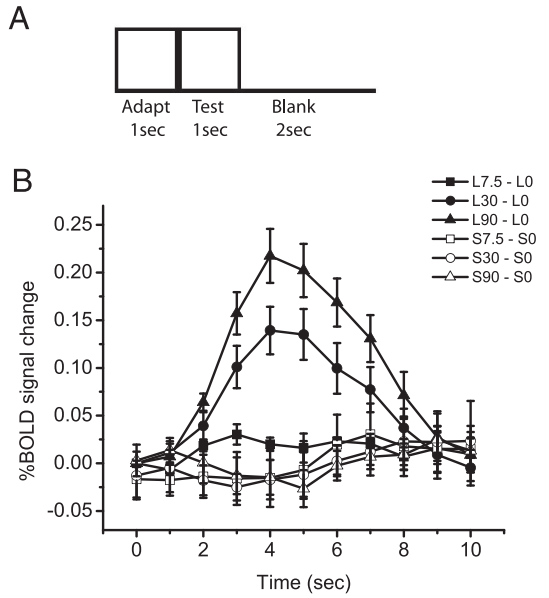

FIG. 4. *A*: schematic of the fMRI short-term adaptation experiment. Adapting stimulus was presented for 1 s, immediately followed by 1-s test stimulus and 2-s blank interval. *B*: comparison of fMRI adaptation effects in V1 between long- and short-term adaptation paradigms. Evoked BOLD signal by the 0° test stimulus has been subtracted as baseline from those by 7.5, 30, and 90° test stimuli. L and S denote long-term and short-term, respectively. Note that, in the short-term adaptation paradigm, adapting and test stimuli were presented at the time-point 0 and 1, respectively.

$R = -0.9691$, $P = 0.0309$; S2: $y = 0.10614 - 0.30302x$, $R = -0.97494$, $P = 0.02506$; S3: $y = 0.10517 - 0.29768x$, $R = -0.98772$, $P = 0.01228$; S4: $y = 0.12822 - 0.34496x$, $R = -0.9515$, $P = 0.0485$; average: $y = 0.1117 - 0.31394x$, $R = -0.98078$, $P = 0.01922$), showing that the magnitude of the fMRI signals in V1 are in close agreement with contrast detection thresholds, even at the level of individual subjects.

DISCUSSION

Using an event-related fMRI design, we studied long-term adaptation to oriented patterns in the human visual cortex. After 20-s preadaptation and 5-s "topping-up" adaptation, the fMRI signal evoked by the presentation of a test stimulus was proportional to the angular difference between the adapting and test stimuli. This response pattern was observed in V1, V2, V3/VP, V3A, and V4. Contrast detection thresholds after adaptation measured in a separate psychophysical experiment were in close agreement with the fMRI magnitudes measured in V1. Our results provide strong neuroimaging evidence for selective adaptation of orientation-tuned neurons in human V1. Specifically, the results suggest that, after prolonged exposure to an oriented grating, the responses of neurons tuned to the adapting orientation are reduced, while neurons tuned to other orientations are less affected. Thus in our experiment, the fMRI signal magnitudes evoked by the test stimuli were proportional to the separation between the orientation tuning curves of the neurons processing the adapting and test stimuli. It should be noted that there was a difference in contrast between the test stimuli in the fMRI (suprathreshold) and psychophysical (near threshold) experiments. Blakemore and colleagues (Blakemore and Nachmias 1971; Blakemore et al. 1973) have shown that, after adaptation, both the threshold elevation with near-threshold test stimuli, and loss of perceived contrast with suprathreshold test stimuli are both tuned to the adapting orientation (but see also, Snowden and Hammett 1992). Because both contrast threshold elevation and fMRI adaptation indirectly measured neural activities of different orientation-tuned neurons, and the comparison is more of a qualitative nature, we feel it is reasonable to compare the psychophysical and fMRI results.

Our result of orientation-selective adaptation in V1 is consistent with the findings of Tootell et al. (1998b). However, from the brief description of their experiment, it is unclear whether attention, which may vary as a function of the degree of change between the adapting and test stimuli, was strictly controlled. This is an important control because it has been well established that attention can modulate fMRI signals in V1 (Brefczynski and DeYoe 1999; Somers et al. 1999; Tootell et al. 1998a; Watanabe et al. 1995). The demanding central fixation task in our study not only helped to equate attention between conditions but also served to promote eye fixation that is important to maintain adaptation in neurons with small receptive fields. It could be argued that attending away from the adapting stimulus (as in our experiment) may attenuate the adaptation effect, but previous psychophysical research has

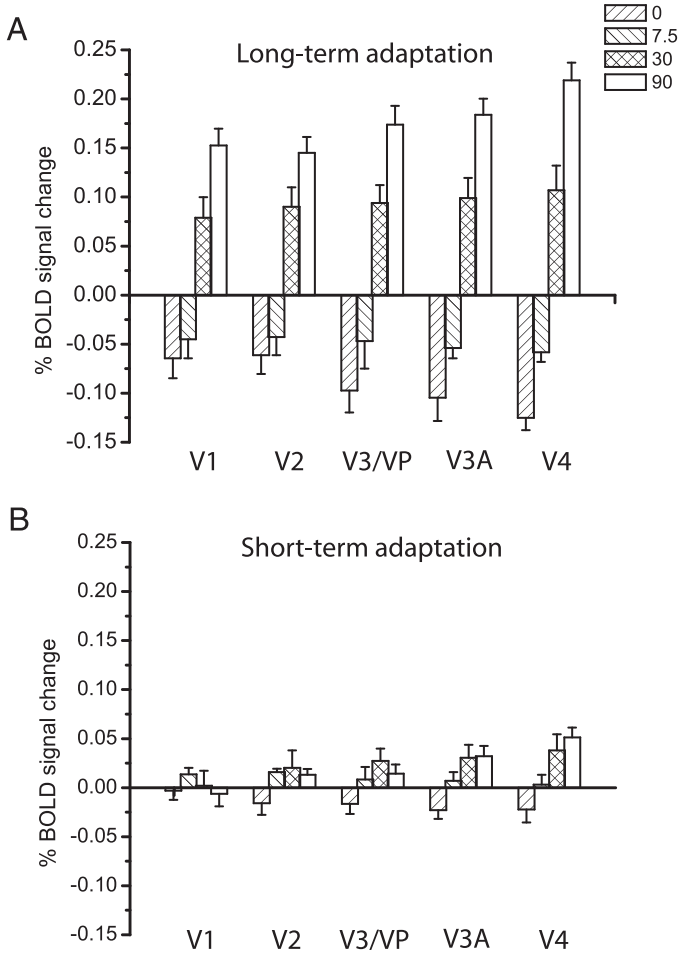

FIG. 5. *A*: peak amplitudes of the event-related BOLD signals in the long-term adaptation experiment. *B*: averaged amplitudes within a 3- to 7-s latency window of the event-related BOLD signals in the short-term adaptation experiment from retinotopic areas, including V1, V2, V3/VP, V3A, and V4. Error bars denote ±SE across 4 subjects.

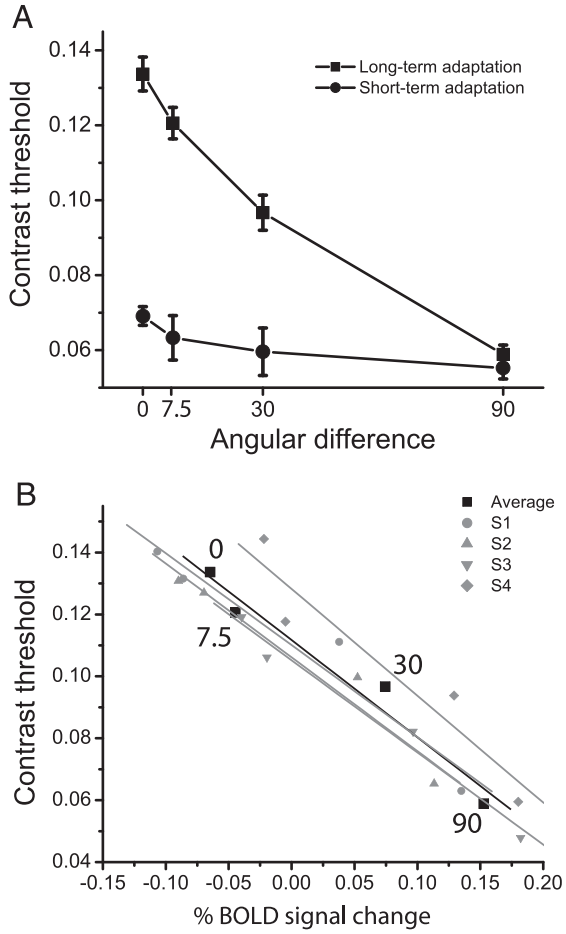

FIG. 6. *A*: contrast detection thresholds for the 0, 7.5, 30, and 90° test stimuli after short-term and long-term adaptation. Error bars denote ±SE across 4 subjects. *B*: contrast detection thresholds after long-term adaptation plotted against peak values of event-related fMRI signals in V1 evoked by 4 different test stimuli in the long-term adaptation experiment. Linear functions were applied to fit individual subject's data (gray lines and symbols) and average (dark line and symbols).

shown that orientation adaptation is largely independent of attention and awareness of the stimulus (He and MacLeod 2001; He et al. 1996; Moradi et al. 2005).

Even with such an attention control task, it could still be argued that the observed monotonic increase of BOLD signals in the long-term adaptation experiment is not caused by adaptation but to transient attention shifts to the test stimuli and/or apparent motion between the adapting and test stimuli. However, there are a number of reasons that argue against these potential explanations. First, in our study, both the adapting and test stimuli comprised multiple Gabor patches with randomized orientations as opposed to a large, single grating (Boynton and Finney 2003; Tootell et al. 1998b). Having localized, distributed peripheral stimuli with a wide distribution of orientations helped to avoid sudden attention shifts from the fixation task during the presentation of the test stimuli. In fact, most subjects reported that they were unaware when orientation changes occurred during the experiment. Second, if the presentation of test stimuli had induced transient attention shifts, we would have expected to observe poorer behavioral performance of the fixation task during test presentation. However, subjects performed equally well at all stages of the trial, suggesting that subjects' attention was evenly distributed throughout the adaptation scans. Third, although sustained attention is very effective in modulating V1 BOLD signal, there is little evidence supporting that BOLD signals in V1 can be effected by transient attention (Liu et al. 2005) and apparent motion (Claeys et al. 2003; Liu et al. 2004). Fourth and most importantly, the short- and long-term fMRI adaptation experiments were identical except for the duration of adaptation. If transient attention and/or apparent motion were the source of the effect in the long-term experiment, we should have also observed a monotonic increase from the 0 to 90° test conditions in the short-term experiment. However, we did not observe any differences between orientation conditions with short adaptation durations. Similar evidence against transient attention and apparent motion explanation can also be found in the long-term adaptation study of Engel (2005).

Unlike our finding of orientation-tuned adaptation in V1 with the long-term adaptation paradigm, Boynton and Finney (2003) did not observe orientation-dependent adaptation in V1 despite showing elevated orientation-specific contrast detection thresholds. Their study used short (1 s) adaptation durations and examined responses to 1-s parallel and orthogonal test stimuli. Our results with short-term adaptation replicated Boynton and Finney's (2003) failure to observe orientation-dependent adaptation in V1. The critical factor for observing orientation-tuned adaptation effects in V1 measured with fMRI seems to be the duration of adaptation. The use of tens of seconds of preadaptation and "topping-up" adaptation is prevalent in psychophysical and neurophysiological adaptation studies. The duration of adaptation influences nearly all dependent measures including the perceptual consequence (Fang and He 2004; Leopold et al. 2002), the strength of the aftereffect (Fang and He 2005; Greenlee et al. 1991; Mather et al. 1998), the length of recovery time (Greenlee et al. 1991), the proportion of adapted neurons in studied neurons (Movshon and Lennie 1979; Nelson 1991), and the shift magnitude of tuning curves (Dragoi et al. 2000; Muller et al. 1999). The failure to detect orientation-specific adaptation in V1 in the study of Boynton and Finney (2003) and ours with short-term adaptation may simply be attributed to V1 neurons not being sufficiently adapted to be detected with fMRI. Our psychophysical results, which show much larger elevations in contrast detection threshold after long-term adaptation, also support this possibility. In addition, the validity of long-term fMRI adaptation has also received strong support from a very recent fMRI study (Engel 2005) in which color-selective neurons with circularly symmetric or oriented receptive fields were shown to be selectively adapted after a 20-s exposure to an adapting pattern. Another recent study (Larsson et al. 2004) also showed orientation-selective adaptation (parallel vs. orthogonal conditions) with a long-term adaptation paradigm. It should be noted that, in light of single-unit studies (Muller et al. 1999; Nelson 1991), short-term orientation adaptation effects in V1 may potentially be observable with fMRI—either with the development of more sensitive imaging methods or by averaging many trials and subjects. For example, using a rapid adaptation design, Kourtzi and Huberle (2005), while not strictly showing orientation tuning in V1, have shown a small release-from-adaptation with 90° orientation changes. Here, we emphasize a strong dependency on timing parameters as well as a large difference in measurability across retinotopic visual areas.

Given that fMRI is an indirect measure of neural activity, it is important to consider the potential source of our signals. Logothetis et al. (2001) suggested that the BOLD signal reflects the input and intracortical processing of a given area rather than its spiking output. The majority of input to V1 is from the lateral geniculate nucleus (LGN) and neurons in LGN are known to have little or no orientation selectivity (Hubel and Wiesel 1961). We can therefore speculate that one source of the orientation-specific signal we observed is from intracortical processing in V1, possibly from orientation-specific synaptic activity between simple and complex cells (Alonso and Martinez 1998). One reason to attribute our results in V1 partially to simple cell activity is that previous neurophysiological studies have shown that complex cells exhibit stronger orientation-specific adaptation to low-contrast than to high-contrast test stimuli (and we used a high-contrast test stimulus). Simple cells, on the other hand, are much less affected by test-stimulus contrast (Movshon and Lennie 1979; Sclar et al. 1989). Other sources could be horizontal connections linking neurons within V1 (Callaway 1998) and feedback from high-level cortical areas (Lamme et al. 1998). Certainly, more studies are needed to better understand the complex relationship between BOLD signals (released from adaptation) and neuronal activities.

Because the effects of long-term adaptation are known to be relatively long-lasting, it is possible that some of the previous scans' adaptation is still present during the successive scan. That is, the cortical areas responsive to a given oriented patch might have reduced responses on the following scan to the orientation that was adapted at that location on the previous scan. In our study, subjects had at minimum 1-min break between adaptation scans. Previous studies (e.g., Greenlee et al. 1991) have shown that adaptation recovery time is approximately equal to the duration of adaptation (20-s preadaptation and 5-s topping-up adaptation in our studies), suggesting that lingering adaptation likely had very small effects on our results. However, it could be possible that larger adaptation effects would have been found if we had not randomized adapting orientations in each adaptation scan.

We observed orientation-specific adaptation in other retinotopic areas including V2, V3/VP, V3A, and V4. One of the perceptual consequences of orientation adaptation is the tilt aftereffect, which can be induced not only by luminance defined stimuli, but also by illusory contours (Paradiso et al. 1989), equiluminous and colored stimuli (Elsner 1978), and random dot stereograms (Tyler 1975). It has been shown that neurons in V2, V4, and V3A are sensitive to these visual properties (Tsao et al. 2003; von der Heydt and Peterhans 1989; Zeki and Marini 1998). Our finding of orientation adaptation across multiple levels of the early visual hierarchy supports the notion that orientation processing is ubiquitous in early areas of the visual system. Future application of our experimental design to other stimulus dimensions and other cortical areas will help understand neural coding at multiple stages of the human visual system.

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