Human visual cortex responds to invisible chromatic flicker

Yi Jiang[1], Ke Zhou[2] & Sheng He[1]

When two isoluminant colors alternate at frequencies of 25 Hz or higher, observers perceive only one fused color. Chromatic flicker beyond the fusion frequency induces flicker adaptation in human observers and stimulates monkey V1 neurons. Here we use functional magnetic resonance imaging (fMRI) to show that many human visual cortical areas, with the exception of VO, can distinguish between fused chromatic flicker and its matched nonflickering control. This result supports the existence of significant intracortical temporal filtering of high-frequency chromatic information. The result also suggests that a considerable difference in cortical activation in many visual cortical areas does not necessarily lead to different conscious experiences.

Humans have a very efficient and powerful visual system, yet both its spatial and temporal resolutions are limited. Spatial patterns that are too fine and temporal fluctuations that are too fast are lost to our perception. In the temporal domain, even under optimal conditions, we cannot resolve luminance flicker faster than about 50 Hz and chromatic flicker faster than 25 Hz[1–4]. Temporal modulations beyond the so-called critical flicker frequencies (CFF) are no longer perceived as flicker. For example, when two isoluminant colors alternate at frequencies of 25 Hz or higher, observers perceive only one fused color. The human visual system consists of multiple levels of neural processing, including retinal and lateral geniculate nucleus stages, and many cortical stages. It is natural to ask where in the system the resolution limit is imposed.

One naive yet intuitive and reasonable prediction of the bottleneck for both spatial and temporal information processing would be that the primary loss of resolution occurs at the link between subcortical and cortical levels of processing. This idea is reasonable because if the information is not eventually perceived, then why bother having the information represented and processed cortically? However, both neurophysiological and psychophysical studies have suggested that invisible information can and does reach cortical neurons. For example, color opponent neurons in V1 of macaque monkeys respond to chromatic flicker at frequencies much higher than the CFF[5]. In psychophysical studies, adapting to either luminance or chromatic flicker at frequencies above their respective CFF can reduce observers' flicker sensitivity[6] and alternating colored patterns too fast to be perceptible can still induce orientation contingent color aftereffects[7]. Recordings of evoked potentials from human subjects also show the so-called entrainment of the signal with the screen refresh[8]. However, single-unit studies generally suffer from severe sampling limitations, and psychophysical as well as VEP studies lack the ability to precisely localize the neural sites. Thus it is challenging for these techniques to investigate responses to fused chromatic flicker across multiple visual areas. Although fMRI studies have investigated cortical responses to chromatic modulation[9], including its temporal properties[10], and demonstrated a correlation between parietal and frontal activation and conscious perception of flicker[11], it remains poorly understood how temporal resolution limitations are imposed in the neural transformation in human visual cortex, especially for chromatic information.

In the current study, we investigated whether the human visual cortex could distinguish fused chromatic flicker from its matched nonflickering control using fMRI. An advantage of the fMRI approach is that measures of cortical responses can be taken simultaneously at multiple cortical areas, thus providing a more complete picture of how the information is processed and transformed in the visual brain. Our results show that fused chromatic flicker generated a substantially higher response compared with a matched nonflickering control stimulus in many early visual cortical areas, with the notable exception of area VO/V8, a region selectively sensitive to color information[10,12].

RESULTS

Retinotopic mapping and ROIs identification

Each subject was first scanned with the standard retinotopic mapping procedure of viewing a rotating wedge and an expanding ring[13]. This allowed us to identify the borders of different visual areas (V1, V2, V3/VP, V3A and hV4/V4v) on a computationally flattened brain (**Fig. 1**). An area just anterior to the hV4/V4v was also identified as a region of interest (ROI). The exact topography and name of this region is still controversial. One model suggests that hV4 (including the foveal part of V4v) contains a complete hemifield representation, and the region anterior to hV4 is labeled VO (VO-1, VO-2)[14], whereas another model treats this region as a distinct region from the V4v representation and names it V8 (ref. 12). Our study does not address the topography of this region and so far we have used an inclusive label VO/V8 to refer to this region anterior to hV4/V4v. For simplicity, we will only use the label

[1]Department of Psychology, University of Minnesota, 75 E. River Rd., Minneapolis, Minnesota 55455, USA. [2]State Key Laboratory of Brain and Cognitive Science, Graduate School and Institute of Biophysics, Chinese Academy of Sciences, 15 Datun Road, Beijing 100101, China. Correspondence should be addressed to S.H. (sheng@umn.edu).
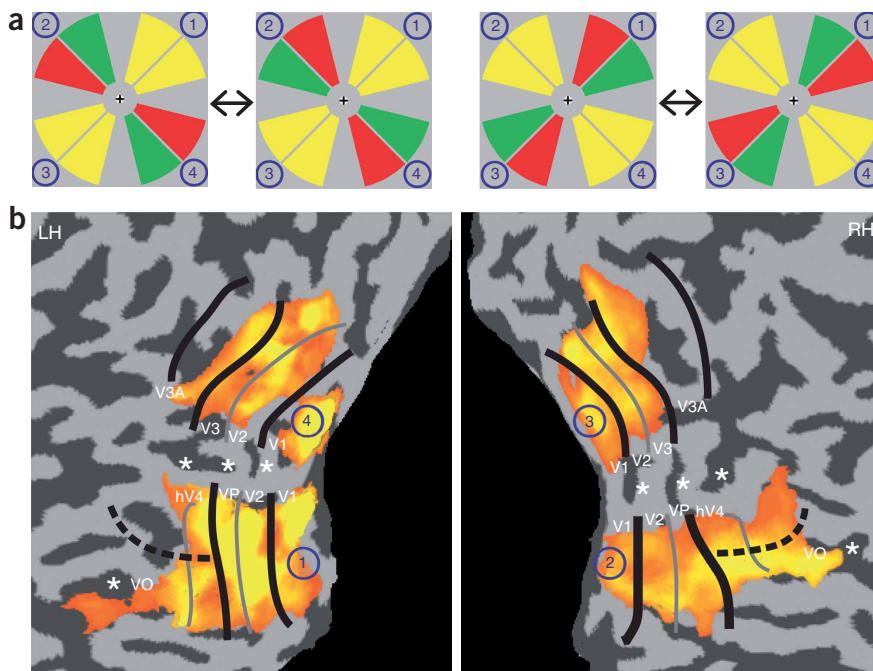
Figure 1 Illustrations of chromatic flicker stimuli and cortical visual areas. (**a**) Chromatic flicker stimuli and matched controls were presented to the four quadrants in the visual field as four pairs of wedges, two counter-phase flickering and two static. (**b**) The corresponding retinotopic regions of chromatic flickering stimuli are depicted on both hemispheres of the flattened brain of a representative observer. Numbers (1, 2, 3 and 4) in **a** and **b** show corresponding locations in space and in the cortex. The boundaries between different retinotopic areas (V1, V2, V3, VP, V3A, hV4/V4v and VO/V8) are indicated with thin gray lines (horizontal meridians) and thick black lines (vertical meridians). The representations of the center of gaze (foveal) are indicated with white asterisks. Dashed lines indicate the boundary of two eccentricity maps associated with the two distinct foveal representations.

$t_4 = 4.82$, $P < 0.01$; V3A: $t_4 = 8.17$, $P < 0.001$; hV4: $t_4 = 4.10$, $P < 0.02$; VO: $t_4 = 1.41$, $P > 0.2$; **Fig. 2b**).

It is of particular interest to compare response patterns in visual areas hV4 and VO, as they are believed to be critical for color selectivity and color perception[10,12,14,15], although the properties of visual field maps in this region are still controversial[12,14]. In the current study, hV4 showed significant activation to the 30-Hz invisible chromatic flicker, but VO did not. In addition, a subthreshold-level 5-Hz chromatic flicker, which also appeared to be static and perceptually matched to the 30-Hz chromatic flicker to observers, did not generate a significantly higher response than the matched control stimulus (V1: $t_4 = 1.07$, $P > 0.3$; V2: $t_4 = 1.01$, $P > 0.3$; V3/VP: $t_4 = 0.75$, $P > 0.4$; V3A: $t_4 = 0.99$, $P > 0.3$; hV4: $t_4 = -0.37$, $P > 0.7$; VO: $t_4 = 0.92$, $P > 0.4$; **Fig. 2b**).

fMRI signal as function of flicker frequency and contrast

The results described above show that human V1 to hV4 can respond robustly to unresolved chromatic flicker compared with perceptually matched static controls. In contrast, VO did not respond differently to the unresolved flicker versus the static control. However, because BOLD activity decreased quite significantly from 5-Hz to 30-Hz flicker in all areas measured, it is possible then that response in VO simply reduced more rapidly compared with other areas as a function of temporal frequency, even before the temporal modulation exceeded the resolution limit. Another possibility is that the contrast response function in VO may be more expansively nonlinear, so that a small reduction in contrast would result in a much more significant decrease in response. Either or both of these two possibilities would explain the different pattern of response found in VO.

We tested both of these possibilities in three subjects by measuring the BOLD response at additional temporal frequencies (5, 15 and 30 Hz) and contrast levels (25, 50 and 100%). These contrast levels were all above flicker detection threshold at 5 and 15 Hz, but were of course below threshold for the 30-Hz flicker. We measured BOLD responses as a function of temporal frequency at three contrast levels (**Fig. 3a**) and BOLD contrast response functions at three flicker frequencies (**Fig. 3b**). The results again showed that V1–hV4, but not VO responded robustly to the fused 30-Hz chromatic flicker, replicating the first experiment. In addition, no support could be found for either of the two alternative
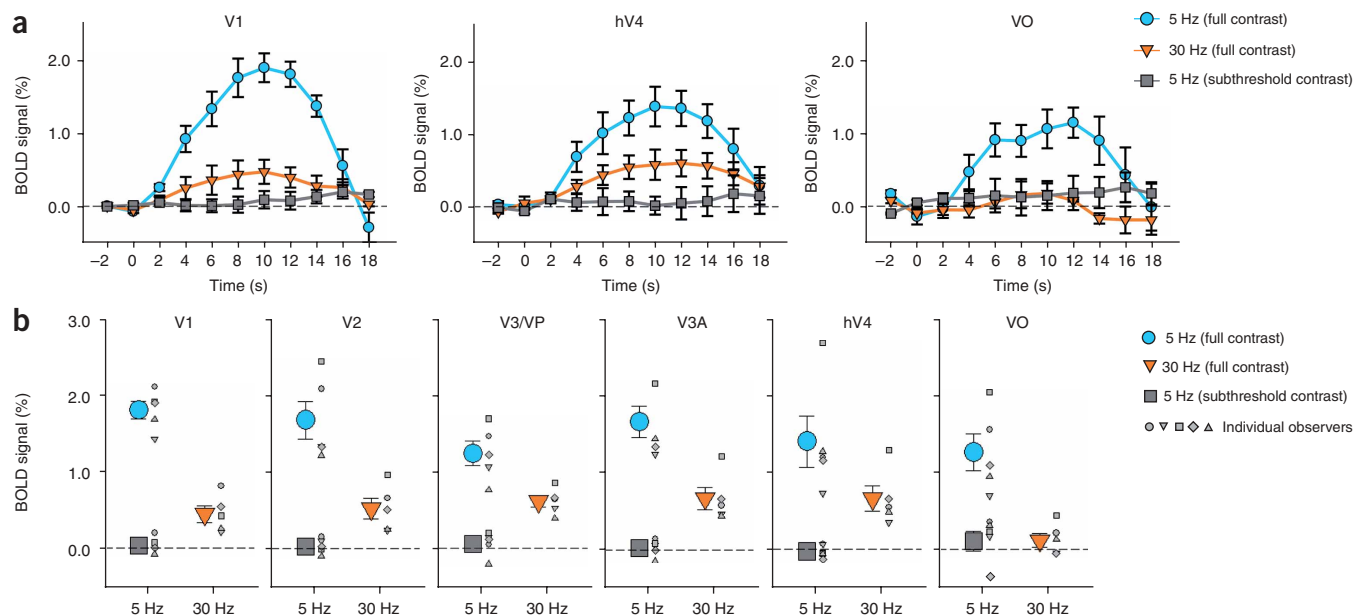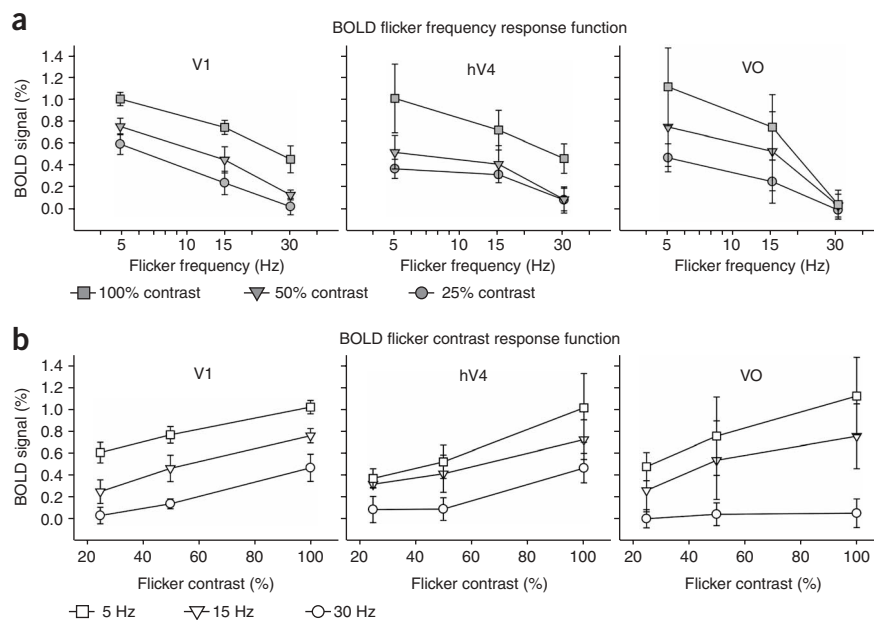
VO, which in our study only includes the region outside the boundary corresponding to the horizontal meridian activation (that is, outside the last thin gray lines in **Fig. 1b**). Thus, the VO in our study does not include the area extending peripherally from V4v, a controversial area according to the two models. We should mention that the pattern of activation found in this excluded part was similar to the near-foveal region of the V4v (or hV4).

Chromatic flickering stimuli and matched controls were presented to the four quadrants in the visual field as four pairs of wedges, two pairs counter-phase flickering and two static (**Fig. 1a**). With the identical spatial configuration, a full-contrast 5-Hz chromatic flicker stimulus was used to localize the retinotopic regions corresponding to the stimuli in visual cortex. We determined the ROIs by combining the retinotopic map and the locations defined by the 5-Hz full-contrast flicker stimulus. Detailed spatial locations of ROIs hV4 and VO for each subject can be found in **Supplementary Table 1** online.

fMRI responses to resolved and fused chromatic flicker

We plotted BOLD signal time courses showing responses for V1, hV4 and VO to three chromatic flickers: 5-Hz flicker at full contrast and at subthreshold contrast, and a 30-Hz flicker at full contrast (example time course, **Fig. 2a**). Time course data are not shown from V2, V3/VP and V3A, because they are very similar to the ones from V1 and hV4. Not surprisingly, compared with the nonflickering static control, the 5-Hz full-contrast chromatic flicker evoked strong cortical responses in each ROI of the visual areas we have identified (V1: $t_4 = 15.67$, $P < 0.0005$; V2: $t_4 = 6.89$, $P < 0.005$; V3/VP: $t_4 = 8.27$, $P < 0.001$; V3A: $t_4 = 7.78$, $P < 0.001$; hV4: $t_4 = 4.24$, $P < 0.02$; VO: $t_4 = 5.32$, $P < 0.01$; **Fig. 2b**). When the flicker frequency was 30 Hz, all four wedges appeared static and observers could not distinguish which two of the wedges were flickering. The BOLD signal measured in the corresponding ROIs of the visual cortex was substantially higher for a 30-Hz fused chromatic flicker compared with a matched nonflickering control stimulus in almost all of the visual areas identified, with the exception of VO (V1: $t_4 = 4.28$, $P < 0.02$; V2: $t_4 = 3.94$, $P < 0.02$; V3/VP:

Figure 2 fMRI responses to 5- and 30-Hz flicker in different visual areas. (**a**) The sample time courses of BOLD signals to chromatic flicker in V1, hV4 and VO. (**b**) Each panel shows the BOLD signals from five individual observers (small gray symbols) as well as the averaged BOLD amplitude (large color symbols) in each visual cortical area. The 5-Hz chromatic flicker with full contrast (cyan circles) evoked strong cortical responses throughout all visual areas identified. The unperceived 30-Hz flicker (orange triangles) also generated a robust BOLD signal in the corresponding retinotopic regions in many early visual areas, with the exception of VO. However, a subthreshold 5-Hz chromatic flicker (gray squares), which was perceptually indistinguishable from the 30-Hz flicker, did not generate a significantly higher response than the matched control stimulus. Error bars indicate ± s.e.m.

explanations that motivated these additional measures. It is also clear that the BOLD signals to chromatic flicker decreased as the temporal frequency of the flicker increased for all of these test contrast levels and in all ROIs (**Fig. 3a**). It is worth noting that between 5 and 15 Hz, the BOLD signal reduction (slope) is comparable across all of these visual areas. Further increasing the flicker frequency from 15 to 30 Hz continued to reduce BOLD signal in V1–hV4 (**Fig. 3a** and **Supplementary Fig. 1** online). However, VO showed a disproportionately large reduction in BOLD signal when flicker frequency was increased from 15 to 30 Hz. The contrast response functions are similar across the different visual areas; neither VO nor the other areas showed dramatically different contrast response functions (**Fig. 3b** and **Supplementary Fig. 1**). The exception, of course, is that there is no measurable response in VO at 30 Hz at any of the contrast levels.

Perceptual equivalency between flicker and control stimuli

A key condition that allows us to interpret the results as indicating that V1–hV4 could still resolve the 30-Hz perceptually fused chromatic flicker is that the fused flicker was perceptually indistinguishable from the static control and the subthreshold 5-Hz chromatic flicker. Before subjects were scanned, they set the isoluminant red and green stimuli using a minimal flicker technique. After the scans were finished, each subject was further tested with a two-alternative forced choice (2AFC) task, determining in each trial which of the two temporal intervals had

Figure 3 BOLD response as a function of flicker temporal frequency and contrast. (**a**) Each panel shows the averaged BOLD signals as a function of temporal frequency at three contrast levels (25%, 50% and 100%) in different visual cortical areas (V1, hV4 and VO). The BOLD signals to chromatic flicker decreased as the temporal frequency of the flicker increased for all of these test contrast levels and in all ROIs. (**b**) Each panel shows the BOLD contrast response function at three flicker frequencies (5, 15 and 30 Hz). The contrast response functions are similar across different visual areas, with the exception of VO, where there is no measurable response at 30 Hz. Error bars indicate ± s.e.m.
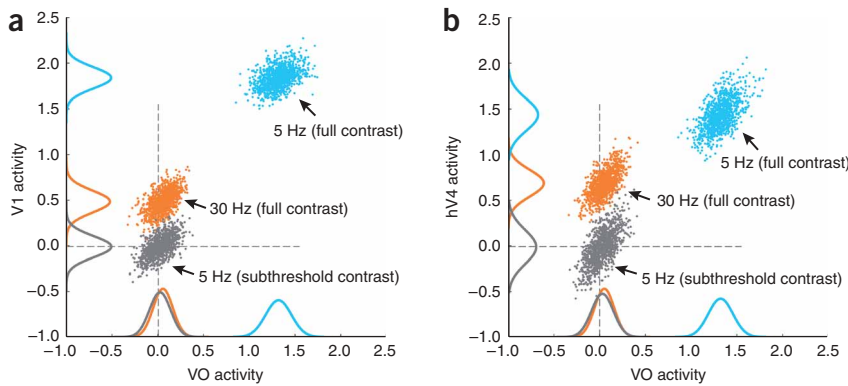
Figure 4 Distribution of fMRI responses to 5- and 30-Hz flicker in different visual areas. A standard bootstrapping procedure is adopted, and the BOLD signals from all of the individual blocks of the primary experiment are resampled with replacement. The bootstrapped sample means for different conditions are shown in the two-dimensional plots. Estimated BOLD signals from V1 (**a**) and hV4 (**b**) are plotted against BOLD signals from VO. 5-Hz full contrast chromatic flicker (cyan), 30-Hz full contrast chromatic flicker (orange) and 5-Hz subthreshold flicker control (gray) could be classified either physically (three conditions) or perceptually (two perceptual categories). BOLD signals in areas V1 and hV4 clearly segregated into three distinct distributions (vertical axes in both plots), whereas in VO there were only two distributions (horizontal axes in both plots) consistent with only two perceptions.

the 30-Hz flickering stimulus while the 30-Hz flicker was presented randomly in either the first or the second interval and the static control or the 5-Hz subthreshold flicker presented in the other interval. Although subjects performed at chance level, discriminating between the 30-Hz flicker and the other two control stimuli, such a result does not rule out the possibility that the 30-Hz flicker stimulus was perceptually different from the static control and the 5-Hz subthreshold flicker.

Thus, we conducted another psychophysical experiment specifically aimed at testing perceptual equivalency between the 30-Hz chromatic flicker and the other two control stimuli. In this task, the stimuli were essentially identical to the ones used during the scan. However, instead of the 30-Hz flicker occupying two wedges and the control stimuli occupying the other two (**Fig. 1a**), we had the 30-Hz flicker occupying three wedges, which left one wedge (randomly selected) as the control stimulus. In each 2-s trial, subjects had to decide which of the four wedges was different from the other three. In other words, subjects could perform this task above chance if the control stimuli were perceived to be different in any way compared with the 30-Hz flicker. In support of the perceptual equivalency between the 30-Hz flicker and the static as well as the 5-Hz subthreshold control, subjects performed at chance level (25%) in these four-alternative forced choice (4AFC) tasks (detailed behavioral results can be found in **Supplementary Table 2** online, see Methods for more details).

DISCUSSION

The visual cortex showed a large BOLD signal when observers viewed a 5-Hz full contrast chromatic flicker. When the flicker frequency was increased to 30 Hz and observers no longer perceived flicker, the invisible flicker still generated a significantly higher BOLD response than did a perceptually matched static stimulus in all of the visual areas that we identified except the region VO (**Fig. 2b**).

To test the possibility that visual cortical areas could respond to subthreshold chromatic flicker in general, rather than a selective intracortical loss of high-frequency information, we also measured BOLD signals to a subthreshold 5-Hz chromatic flicker in the same scans. This subthreshold 5-Hz chromatic flicker was perceptually

indistinguishable from the 30-Hz chromatic flicker to observers (this was verified with an objective 2AFC task as well as a 4AFC task, see Methods for details). Results show that the response to the 5-Hz subthreshold flicker was not different from that of the matched static wedges in all visual areas. In other words, observers had the same perception of static wedges for the 5-Hz subthreshold flicker, the 30-Hz full contrast flicker and the physically static wedges, yet their visual brain responded more strongly to the 30-Hz flicker than to the other two matched stimuli.

One possible model of the cortical representation of chromatic flicker is that the flicker signal goes through increasing levels of filtering from V1 to V2, V3/VP and so forth. Such a model would predict that the magnitude of the neural response to the chromatic flicker, especially at high temporal frequencies, would decrease as the flicker signal ascends from primary visual areas to extrastriate areas. However, the magnitude of the BOLD signal from V1 to V2, V3/VP and hV4 changes very little for either 5- or 30-Hz chromatic flicker; the insensitivity to rapid chromatic flicker is specific to VO (**Fig. 2b**). Given the complex origin and nature of the fMRI BOLD signal[16], one needs to be cautious when interpreting the magnitude data. Quantitative interpretation aside, it is clear in the current study that the visual brain responds to the fused and invisible chromatic flicker not only in V1, but in many other visual areas as well. More importantly, although there was little change in the response magnitude from V1 to hV4, a qualitative change in response occurred between hV4 and VO. When the observers were not perceiving the 30-Hz flicker, the activity in VO was unable to distinguish a 30-Hz flicker from a static control. This finding is consistent with a recent imaging study that revealed significant chromatic (red-green) low-pass temporal filtering in VO, but not in V1 and other early visual areas[10].

The hV4 and VO regions have been suggested to be critical for color selectivity and color perception[10,12,14,15], and it is also likely that this area was damaged in achromatopsic patients reported in clinical studies[17–19], although researchers are yet to reach consensus on the functional properties and anatomical definition of this area[12,14]. The area labeled as V8 (which significantly overlaps with the VO defined in this paper) selectively responds to illusory colors[12]. Furthermore, early studies revealed an area anterior to V4, but not V4 itself, in the right fusiform gyrus that is selectively activated during color-imagery in both normal sighted subjects[20] and a blind patient[21]. In the current study, hV4 responded to both the visible 5- and 15-Hz chromatic flickers, and the invisible 30-Hz chromatic flicker, whereas VO was activated in response to the visible 5- and 15-Hz flicker, but not the invisible 30-Hz flicker. This pattern of current results, combined with previous investigations, suggests that VO has a critical role in the conscious representation of chromatic information, whereas hV4 and earlier areas process color-related information more independently of the observers' awareness state. To highlight this point, the bootstrapped BOLD signal distributions based on all of the individual blocks from the primary experiment are shown in two-dimensional plots (**Fig. 4**)[22,23]. We plotted BOLD signals from V1 (**Fig. 4a**) and hV4 (**Fig. 4b**) against BOLD signals from VO. Data from V2 and V3/VP are not shown here, as they are similar to data from V1 and hV4. The three stimuli (5-Hz

full contrast chromatic flicker, 30-Hz full contrast chromatic flicker, 5-Hz subthreshold flicker control) could be classified either physically (three conditions) or perceptually (two perceptual categories). BOLD signals in areas V1 and hV4 clearly segregated into three distinct distributions, whereas in VO there were only two distributions consistent with only two perceptions.

The results suggest that considerable differences in cortical activation in early visual areas do not necessarily lead to different conscious experiences. Much effort has been devoted to the role (or the lack thereof) of V1 in visual awareness. One of the strongest pieces of evidence suggesting that V1 is not part of the neural correlates of consciousness is that responses in V1 exhibited variation between perceptually equivalent conditions[5,6,24–26]. This is straightforward, yet admittedly simplistic logic[27]. Given that almost all of the visual areas responded to the invisible flicker, according to the same simple logic, one would need to conclude that all of these areas are not part of the neural correlates of consciousness. Alternatively, visual awareness may always require the participation of multiple visual areas with both feedforward and feedback connections[28–32]. Given such a model, no area by itself is sufficient to support visual awareness. One should not rule out a given cortical area as a participant in the neural correlate of visual awareness simply on the basis of the observation that such an area shows 'unconscious activation'.

In summary, results show that many of the human visual cortical areas, with the exception of VO, can distinguish between fused chromatic flicker and its matched nonflickering control. Apparently, considerable differences in cortical activation in visual cortical areas do not necessarily lead to different conscious experiences.

METHODS

Participants. Five healthy subjects (two male) participated in the primary experiment, and two of them and another naive subject participated in the additional experiment to examine the BOLD response as a function of flicker temporal frequency and contrast. All 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.

Stimuli and procedure. Stimuli were presented through a LCD projector (SANYO, Model PLC-XP41/L) onto a rear projection screen located behind the participant's head inside the magnet bore. The rise and fall times of the LCD projector are about 10 ms and 2 ms, respectively, which was sufficiently fast to allow the signal to reach peak modulation even at 30 Hz. The screen was viewed with an angled mirror positioned on the head-coil. A central cross ($0.3° \times 0.3°$) was always presented to subjects serving as the fixation. The stimuli consisted of four wedges with each wedge extending to a visual angle of $3.5°$ in one of four quadrants (see **Fig. 1a**). Each wedge also subtended a polar angle of $62°$ and was distributed symmetrically along the diagonal axis. Two of the wedges in the opposite direction were filled with isoluminant red (with chromatic CIE *xy* coordinates of [0.523, 0.462]) and green (with chromatic CIE *xy* coordinates of [0.343, 0.638]) colors with each color occupying one side of the diagonal line (for example, the wedges in the second and the fourth quadrants as shown in the left side of **Fig. 1a**); in these wedges, the isoluminant red and green lights were synchronously exchanged at the flicker frequency. The other two (for example, the wedges in the first and the third quadrants as shown in the left side of **Fig. 1a**) were filled with a uniform and static yellow color with the mean luminance of the red-green flicker. Thus there were two possible presentation conditions for the chromatic flicker: the first/third quadrants and the second/fourth quadrants. The whole wedge pattern was superimposed on a uniform field whose intensity was equal to the mean luminance of each wedge (824 cd m^{-2}). The viewing distance was 102 cm.

In the primary experiment, there were three flickering conditions (5-Hz flicker with full contrast, 30-Hz flicker with full contrast and 5-Hz flicker with subthreshold contrast) and two possible display positions (the first/third

quadrants and the second/fourth quadrants), resulting in six combinations. For each condition, stimuli were presented in a block design comprised of a 12-s probe followed by 12-s of uniform background. The 24-s cycle time was chosen to minimize the effect of interference between the undershoot at the end of one hemodynamic response with the start of the following one. A total of 18 blocks (each condition was repeated three times in a truly randomized order) were presented in each run, and an additional 8-s blank period was added at the start of the scan to minimize transient magnetic saturation effects. Thus, the total scan time for each run was 440 s. The participants were asked to do a demanding fixation task (detecting a slight change in the orientation of the fixation cross) throughout each run to facilitate stable fixation and to help maintain their attention at the center of the display. The fixation cross changed at random time points (on average once every 1 s), independent of the flickering stimulus presentation.

The study with additional frequency and contrast conditions was similar to the primary study, except for the sampling of more temporal frequency (5, 15 and 30 Hz) and contrast conditions (25%, 50% and 100%). For each condition, stimuli were presented in a block design comprised of a 12-s probe followed by 12 s of uniform background, with the order of different conditions randomized across runs. The participants were asked to do the same demanding fixation task as in the primary study (detecting a slight change in the orientation of the fixation cross) throughout each run to facilitate stable fixation and to help maintain their attention at the center of the display.

Red-green isoluminance. Flicker photometry was used to select the isoluminant red and green stimuli for the chromatic flicker. Observers viewed a $3.5°$ circular patch with alternating red and green colors in the scanner before the fMRI experiment. The two colors were counterphase-modulated at 30 Hz, a frequency too fast for observers to track the color alternation. With the contrast of red color fixed, the red/green alternation generally appeared as achromatic flicker, but each observer could adjust the contrast of green color so that no flicker could be detected. Observers were instructed to make settings in both directions: gradually increasing the green color contrast or gradually decreasing it.

2AFC flicker detection and 4AFC stimulus discrimination. Because the interpretation of the study depends critically on the 30-Hz chromatic flicker being truly fused and perceptually identical to the control conditions, we also tested flicker detection in a criterion-free manner. All participants underwent a 2AFC experiment in separate sessions in the scanner after the fMRI experiment. The experimental situation (contrast, luminance, viewing angle, etc.) was exactly the same as the functional imaging experiments. For each trial in the 2AFC experiments, there were two successive temporal intervals (2 s each, with a 500-ms blank gap between them). The 30-Hz full contrast flicker, the 5-Hz subthreshold flicker or the matched static control stimulus were presented randomly in the first or the second interval, and one of the others was presented in the other interval. Observers pressed one of two buttons to indicate which interval (the first or the second) had the flickering stimulus. All observers performed at chance level for all of the comparisons (30-Hz full contrast flicker with static control stimulus, 5-Hz subthreshold flicker with static control stimulus and 30-Hz full contrast flicker with 5-Hz subthreshold flicker).

Because the 2AFC results primarily supported the notion that the 30-Hz flicker was not perceived as flickering, we performed another 4AFC test using the spatial layout essentially identical to that used during fMRI scanning to test perceptual equivalency between the 30-Hz chromatic flicker and the other two control stimuli. One of the four wedges was static (or 5-Hz subthreshold flicker), whereas the other three were the 30-Hz full contrast flicker. After each 2-s trial, observers indicated which wedge they believed was different than the other three. All observers performed at chance level (25%; see **Supplementary Table 2**).

fMRI data acquisition and analysis. MRI data were collected on a 3T Siemens Trio outfitted with an 8-channel phase-array coil. Echoplanar data were acquired with standard parameters (28 axial slices, 3.0 mm thick; field of view, 220×220 mm^2; matrix, 64×64; repetition time, TR, 2,000 ms; echo time, TE, 30 ms; flip angle, $75°$). The first four volumes were discarded to allow for magnetization equilibration. A T1 weighted anatomical volume (3D MPRAGE; $1 \times 1 \times 1$ mm^3 resolution) was acquired for localization and visualization of the functional data.

After motion correction (SPM99, http://www.fil.ion.ucl.ac.uk/spm), the functional data were coregistered with the anatomical scan using BrainVoyager

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QX (Brain Innovation). After regions of interest (ROIs) were defined, time courses from each ROI were extracted and imported into Matlab for further analyses. For each scan, we averaged the signal intensity across trials for each condition at each of 11 time points (from –2 s to 18 s). These time courses for each condition were then averaged across scans. The BOLD signal (flickering wedges minus static wedges) was calculated using average signals between 8 and 12 s in each time course (condition) for each subject, as the signal usually took 6–8 s to rise to the full magnitude.

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

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