Supporting Information

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SI Text

Entrainment of Neural Activity in the Visual Cortex with High-Frequency Flicker. Recent work has provided clear evidence that high-frequency temporal properties of a stimulus are reflected in neural activity in the visual cortex. EEG responses in visual cortex and single-cell responses of V1 neurons display phase locking to periodic input at frequencies of up to 100 Hz (1, 2). In a persuasive article, Williams *et al.* (1) reported single-cell recordings from V1 of macaque monkeys, revealing entrainment at up to 100 Hz (Fig. S1*a*; the highest frequency tested); this is twice the highest frequency used in our experiment. In another study, Herrmann (2) measured steady-state visual evoked potentials (SSVEPs) and demonstrated that unstructured visual stimulation can entrain responses in visual cortical neurons at rates in excess of 50 Hz (Fig. S1*b*). In addition to confirming this, by recording a very sharp peak in the power spectrum at 60 Hz (Fig. S1*a*), Williams *et al.* (1) found that entrainment to flicker depends on the configuration of the stimulus: high-contrast structured stimuli (gratings and checkerboards) lead to stronger phase locking than unstructured stimuli (uniform illumination). Our stimuli are high-contrast Gabor patches (thought to be optimal for driving V1 cells) and would thus result in this type of entrainment.

Visual monitoring and display of temporal modulations. In all our experiments the visual presentation was controlled by a VS2/5 Cambridge Systems graphics card, which allows high temporal precision at a resolution of the CRT monitor refresh rate (maximum 140 Hz, for our CRT). Here, we present, for reasons of validation, a tracked signal of the luminance level for a 100-ms interval during the cueing period of the display, by using a DSO-8500 digital storage oscilloscope (Link Instruments) and a light-to-voltage converter (TKK Brain Research Unit).

Fig. S2*a* shows measurements of the output of a patch flickering at 50 Hz, and Fig. S2*b* shows the modulation for a "nonflickering" distractor; the sensor was placed on a high-luminance area of the Gabor, which results in an increase relative to the background gray level. Peaks can be seen in the amplitude of the signal, occurring at regular 10-ms intervals that correspond to the 100-Hz monitor refresh rate. Additionally, a high-amplitude 50-Hz peak can be observed for the cue flicker, whereas the distractor always has a constant output. Note that the mean response amplitude for the distractor (dashed horizontal line) is approximately equal to the mean response amplitude of the cue flicker, leading to the appearance of equal contrast for cue and distractor.

Fig. S3 shows identical measurements of monitor output for the 30-Hz modulation. The monitor refresh rate is 120 Hz. In this case, regular peaks occur every 8.3 ms, but for the cueing patch two consecutive high-amplitude frames are followed by two low-amplitude frames, thus generating a cueing frequency of 30 Hz. The measurements demonstrate that the mean distractor response amplitude (horizontal dashed line) is approximately equal to the mean response amplitude of the cue.

Cueing Effect for Additional Frequencies Between 30 and 50 Hz. In addition to the 30-Hz vs. 50-Hz comparison presented in the main text, we also measured, for a smaller sampler of observers, the cueing effect of flicker at two intermediate frequencies, 35 Hz (distractors at 140 Hz) and 40 Hz (distractors at 80 Hz). The results, presented in Table S1, show a large congruency effect for cueing frequencies of both 40 Hz (28 ms) and 50 Hz (23 ms). For lower frequencies, the effect is reduced (9 ms for 35 Hz) or absent (3 ms for 30 Hz; as reported in the main text, this is nonsignificant).

Relationship Between Congruency Effect and Flicker Detection Score. Fig. S4 shows a scatter plot of the correlation between the congruency effect and the flicker detection rate with 50-Hz ($r = 0.08$, $P = 0.74$) and 30-Hz flicker ($r = 0.06$, $P = 0.79$). As can be seen, there is no indication that the 50-Hz congruency effect is caused by trials in which observers perceived the flicker; if this were the case, observers with a higher flicker detection rate would exhibit a larger congruency effect.

Extension to Other Types of Target: Contrast Modulation and Dot Probe. Individual subject data for two tasks involving new target features are presented below. Reaction times were measured in response to a contrast change-target (Table S2), and detection accuracies were measured in response to a briefly presented dot probe (Table S3; see *Materials and Methods* for additional details).

1. Williams PE, Mechler F, Gordon J, Shapley R, Hawken MJ (2004) Entrainment to video displays in primary visual cortex of macaque and humans. *J Neurosci* 24:8278–8288.
2. Herrmann CS (2001) Human EEG responses to 1- to 100-Hz flicker: Resonance phenomena in visual cortex and their potential correlation to cognitive phenomena. *Exp Brain Res* 137:346–353.

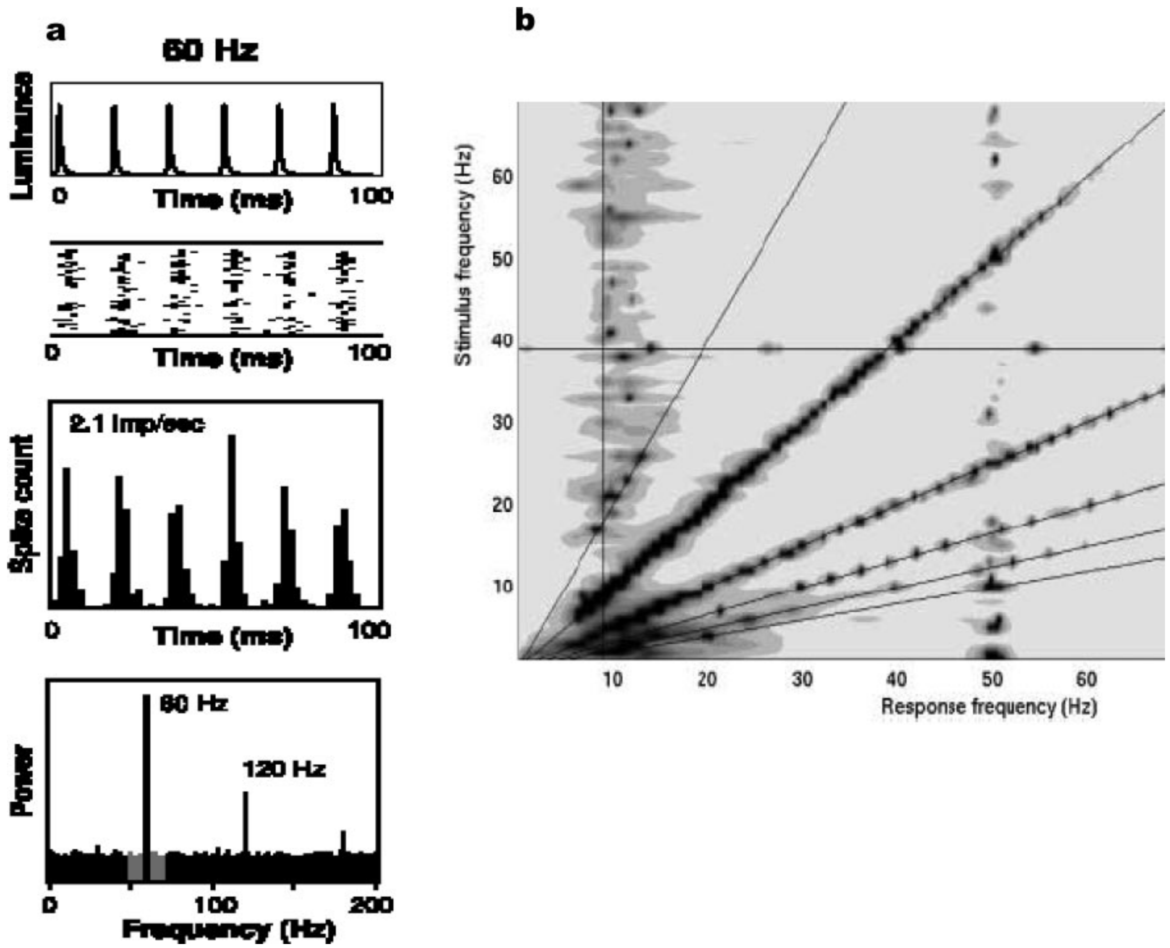

Fig. S1. High-frequency neural entrainment in the visual cortex. (*a*) Single-unit responses displaying phase locking to a 60-Hz CRT monitor, recorded in monkey V1 (3; Fig. 2). In response to 60-Hz periodic input, one obtains a very sharp peak in the neuronal power spectrum at the same frequency. (*b*) Data from Herrmann (2) displaying SSVEPs to a range of stimulus frequencies, by using unstructured illumination of the entire visual field by means of LEDs. Response frequency (*x* axis) is shown as a function of stimulation frequency (*y* axis). Main diagonal line = fundamental frequency. [*a* and *b* reproduced with kind permission from Springer Science + Business Media: *Experimental Brain Research*, Human EEG responses to 1–100 Hz flicker: Resonance phenomena in visual cortex and their potential correlation to cognitive phenomena, vol. 137, 2001, pp 346–353, Christoph S. Herrmann, figure 5.]

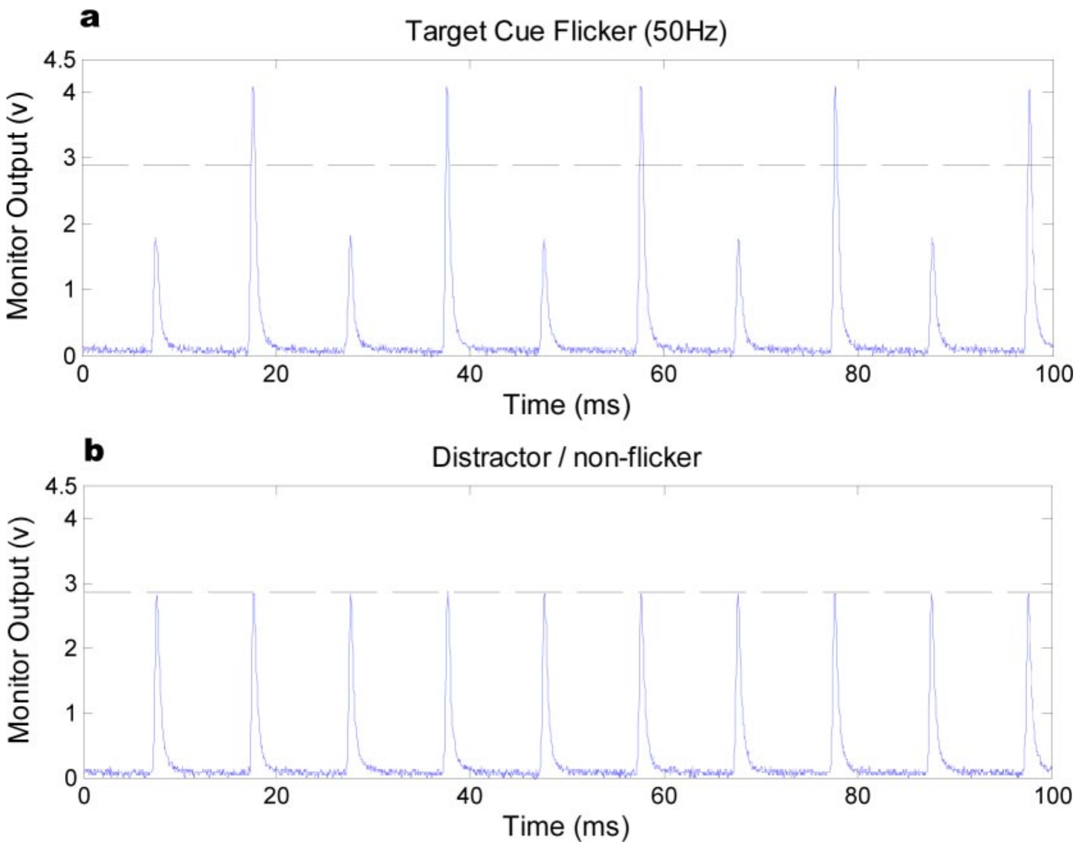

Fig. S2. Target cue flicker (50 Hz) (*a*) and distractor/nonflicker (*b*), using a refresh rate of 100 Hz.

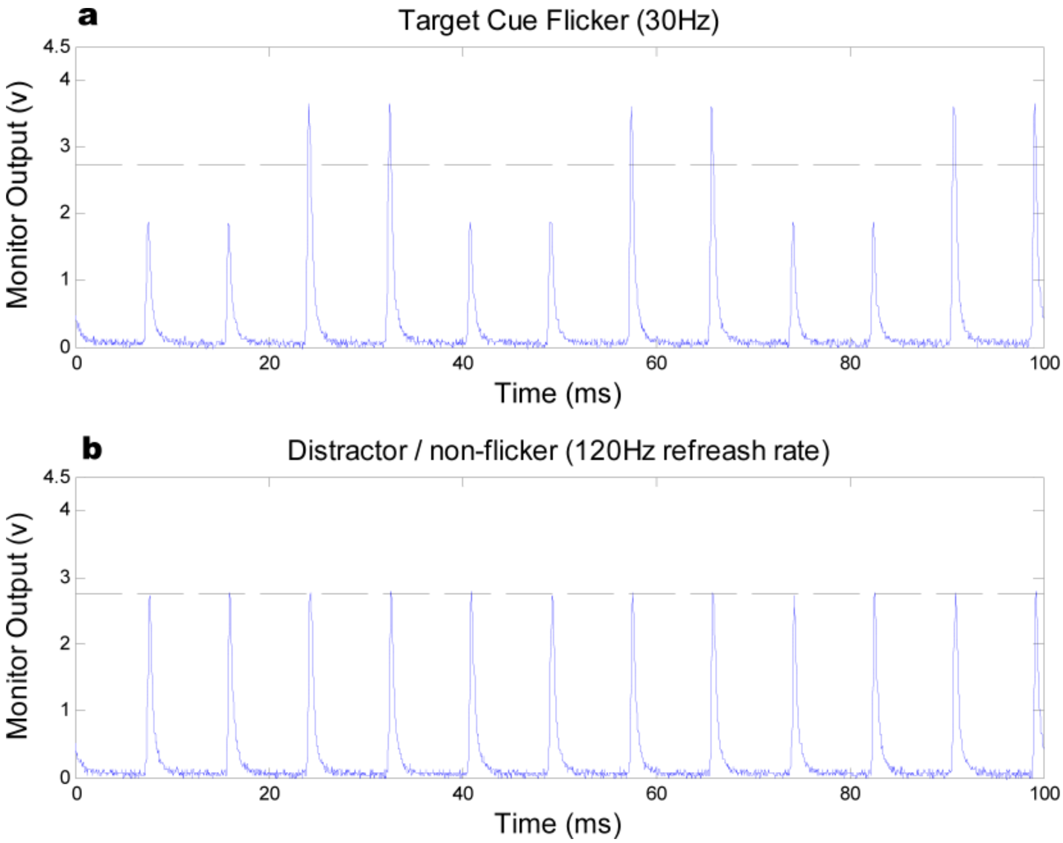

Fig. S3. Target cue flicker (30 Hz) (*a*) and distractor/nonflicker (*b*), using a refresh rate of 120 Hz.

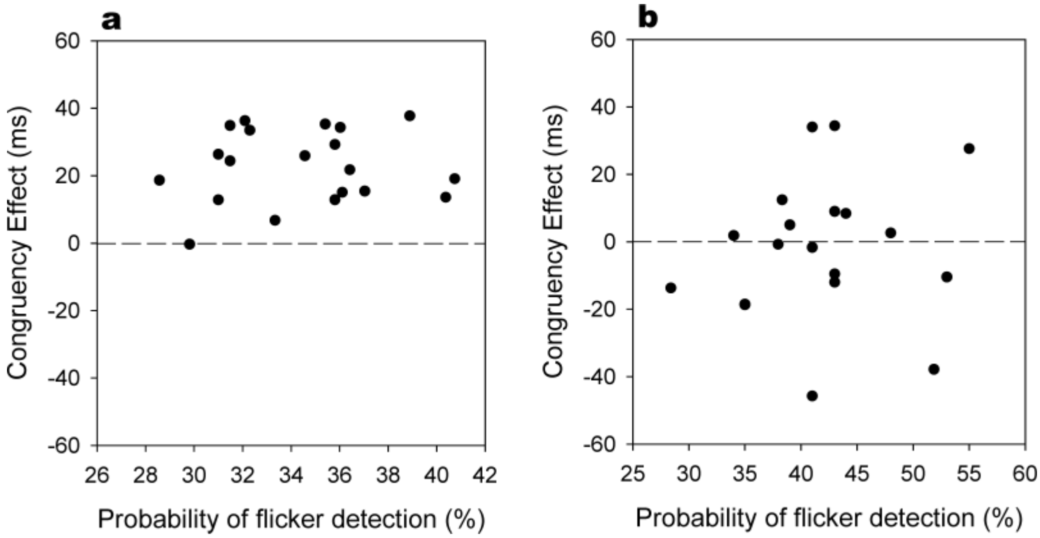

Fig. S4. Scatter plot of 50-Hz (*a*) and 30-Hz (*b*) congruency effects as a function of the flicker detection rate for individual observers. Note that the detection rates plotted in *b* are obtained from a separate session to the staircase that was used to set the contrast modulation. The dashed horizontal line indicates the 0-ms congruency effect level.

Table S1. Summary of results for all frequencies examined

Frequency, Hz	30	35	40	50
RT congruent, ms	493	463	460	483
RT incongruent, ms	496	471	488	506
Congruency effect, ms	3	9	28	23
SE of mean, ms	7	4	8	4
Detection rate, %	42	38	40	33

Frequencies of 30 and 50 Hz were tested with the same 20 subjects; 35- and 40-Hz frequencies were tested with groups of 5 subjects. The difference in mean RTs for the 35- and 40-Hz compared with the 30- and 50-Hz conditions is caused by a smaller, and more experienced, group of observers in the former conditions.

Table S2. Reaction times of 7 observers to the contrast modulation target

Subject no.	Congruent, ms	Incongruent, ms	Congruency effect
1	408	429	21
2	481	512	31
3	478	504	26
4	610	623	13
5	374	406	32
6	511	541	30
7	524	573	48
Mean	484	513	29

Table S3. Accuracies (% correct) of six observers in the dot probe detection task

Subject no.	Congruent, %	Incongruent, %	Congruency effect
1	84	78	6
2	79	65	14
3	80	68	12
4	84	84	0
5	78	68	10
6	59	51	9
Mean	77	69	9