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Visual Flicker in the Gamma-Band Range Does Not Draw Attention

Rosanne M. van Diepen,[1,2] Sabine Born,[1] David Souto,[1,3] Angélique Gauch,[1] and Dirk Kerzel[1]

[1]*Faculté de Psychologie et des Sciences de l'Éducation, Université de Genève, Genève, Switzerland;* [2]*Rudolf Magnus Institute of Neuroscience, University Medical Center Utrecht, Utrecht, The Netherlands; and* [3]*Cognitive, Perceptual and Brain Sciences, University College London, London, United Kingdom*

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van Diepen RM, Born S, Souto D, Gauch A, Kerzel D. Visual flicker in the gamma-band range does not draw attention. *J Neurophysiol* 103: 1606–1613, 2010. First published January 20, 2010; doi:10.1152/jn.00629.2009. External transients, such as a flash or a startling sound, are believed to capture attention. Bauer, Cheadle, Parton, Müller, and Usher reported that attention can also be captured by a stimulus that flickers subliminally at 50 Hz, presumably by entrainment of neurons to the flicker frequency. In their reaction time (RT) task, participants had to locate a subtle change in the spatial frequency content of one of three Gabors (the target). Prior to target onset, presumably subliminal 50-Hz flicker in one of the Gabors served as a spatial cue. Bauer et al. found faster RTs when the cued location was congruent with the target location than when the cue was incongruent with the target location. In their experiments, the cue stopped to flicker at 50 Hz at target onset and was replaced by a stimulus flickering at 100 Hz (i.e., the screen refresh rate). In the present study, we show that the transition from 50 to 100 Hz results in a flash-like impression that can be localized above chance. We suggest that the illusory transition flash interfered with the localization of the subtle target, which contributed to the congruency effect. In support of this view, participants selected the flickering object more often than the non-flickering object when they failed to respond to the target. Further, no cueing effects were observed when the cue continued to flicker until the end of the trial or when the target was a salient change in polarity. In our view, the cueing effect occurs because observers confuse the illusory transition flash with the target when the two are similar. When truly subliminal flicker is used (70-Hz flicker), very small cueing effects persist in the absence of an illusory transition flash but may be accounted for by small effects on reaction time unrelated to attention.

INTRODUCTION

Attention selects relevant sensory information for detailed processing while suppressing irrelevant information. Selection is necessary because resources for cognitive processing are limited. In behavioral research, the influence of attention can be observed in faster reaction times (RTs), better accuracy, and increased sensitivity to subtle changes (overview in Johnson and Proctor 2004). As a neural correlate of attention, increased neural synchronization in the gamma band (30 –100 Hz) has been proposed (overview in Womelsdorf and Fries 2007). According to this idea, attention modulates the neural firing rhythm such that a local functional group of neurons that process the specific features of an attended stimulus synchronize their responses. Synchronization of neuronal firing can increase the summation of postsynaptic potentials in target cells and in this way increase their impact on downstream areas.

Bauer et al. (2009) found supporting behavioral evidence for a causal link between synchronization of neurons in the gamma band and attentional selection. They exploited the finding that neurons in the visual cortex synchronize their firing rates to the frequency of a flickering light (Herrmann 2001; Williams et al. 2004). In a set of experiments, Bauer et al. suggested that a cue flickering at a frequency in the midgamma band (40–70 Hz) attracts attention due to neural entrainment at the flicker frequency. In line with their hypothesis, stimuli cued by 50-Hz flicker were processed more efficiently than stimuli that were flickering at 100 Hz. Further, their results suggest that shifts of attention by entrainment occurred without conscious perception of the flicker. Therefore attention was attracted by the temporal modulation itself and not by top-down intention or a salient sensory event that typically underlie shifts of attention. Taken together, Bauer et al.'s results may be important because they pave the way for direct psychophysical investigations of the behavioral consequences of neuronal gamma-band synchronization: their methods would allow researchers to externally induce a neural firing rate that is thought to underlie attention.

In Bauer et al.'s (2009) experiments, participants were asked to indicate the location of a subtle change in spatial frequency in one of three Gaussian-windowed sine-wave gratings (Gabor patches) by making a speeded key press (i.e., a reaction time task; see Fig. 1). Before the change in spatial frequency occurred, one of the Gabors flickered at a frequency of 50 Hz (flicker cue) for 1 s. The remaining Gabors were shown at a frequency of 100 Hz (i.e., the refresh rate of the screen). The time-averaged contrast of 50% was equal for all Gabors. The location of the flicker cue was either the same (congruent) or different (incongruent) from the location of the change in spatial frequency. Participants responded faster with congruent than with incongruent flicker cues. This suggests that attention was shifted toward the 50-Hz flicker cue. The cueing effect was observed even though the 50-Hz flicker was supposed to be subliminal: in a subsequent cue localization task, participants were unable to distinguish between Gabors flickering at 50 and 100 Hz. Moreover, aperiodic flicker or visible flicker outside the gamma range (25 and 30 Hz) did not produce any cueing effects in reaction times. Bauer et al. suggested that attraction of attention only occurred in the midgamma band (40–70 Hz) but not at the extremes of the gamma band (i.e., at 25, 30, or 100 Hz).

In the present contribution, we question conclusions by Bauer et al. (2009). First, we doubt that the observed cueing effects were exclusively caused by 50-Hz flicker. In their RT

Address for reprint requests and other correspondence: D. Kerzel, Faculté de Psychologie et des Sciences de l'Éducation, Université de Genève, 40 Boulevard du Pont d'Arve, CH – 1205 Genève, Switzerland (E-mail: dirk.kerzel@unige.ch).

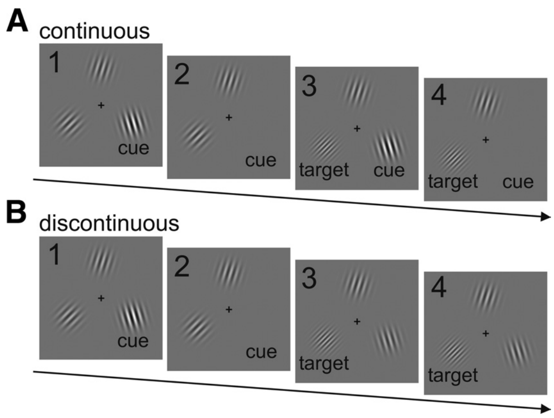

FIG. 1. Example sequence of stimulus displays (not drawn to scale) to create 50- and 100-Hz flicker. Successive frames (from 1–4) are separated by 10 ms. Frames 1 and 2 show the cue frames. In the experiment, the 2 frames alternated at a screen refresh rate of 100 Hz. Thus the cue was flickering at 50 Hz (i.e., the cued Gabor was shown at 100% contrast every 20 ms). In the graph, the cue is always shown in the lower right position. After cue onset, frames 3 and 4 alternated to present the target. The target was an increase in the spatial frequency of 1 Gabor. Here the magnitude of the frequency change is exaggerated for better visibility. Both panels show incongruent trials in which cue and target positions are different (i.e., cue in lower right and target in lower left position). *A*: the 50-Hz flicker continues after target onset (continuous flicker). *B*: the 50-Hz flicker cue alternating between 100 and 0% contrast is replaced by 100-Hz flicker at 50% contrast (discontinuous flicker). At the transition between 50- and 100-Hz flicker, an illusory flash is perceived.

task, the 50-Hz flicker ended with target presentation and was replaced by 100-Hz flicker. When we replicated the stimuli, we noted that the transition from 50 to 100 Hz in the cued Gabor produced a flash-like impression. This phenomenon will be referred to as illusory transition flash (see Fig. 1). Recordings with a high-speed camera confirmed that the flash was not present on the screen but resulted from visual processing. We think that the illusory transition flash contributed to the congruency effect and was confounded with effects of the flicker cue in Bauer et al.

Second, we doubt that the 50-Hz flicker cue was truly subliminal. Bauer et al. (2009) claimed that the flicker was not consciously perceived based on a cue localization task without transition from 50- to 100-Hz flicker. Further, Bauer et al. (2009) added stimuli flickering at 25 Hz in the cue localization task to keep their participants motivated. In our view, this may have induced participants to look only for the clearly visible 25-Hz flicker while discouraging them from trying to find the 50-Hz flicker. Also no feedback was given such that observers never knew whether they were looking for the correct feature. In this study we demonstrate that the visibility of the 50-Hz flicker is underestimated for the abovementioned reasons. Stimuli generated at a higher monitor refresh rate (140 Hz instead of 100 Hz), which yield truly subliminal flicker were then re-examined in the RT task.

METHODS

Participants and procedure

All participants were undergraduate or graduate students at the University of Geneva who participated to fulfill a course requirement or to earn 20 Swiss francs (~19 US dollars). Participants reported visual acuity within normal limits. After participants gave their written informed consent, the task was explained, and some practice trials were administered. If not stated otherwise, a short break was given after each block of ~48 trials. One participant was tested in *experiments 4* and *5.* The remaining participants were not tested in more than one experiment. All procedures were approved by the faculty's ethics committee in accordance with the 1964 Declaration of Helsinki.

Apparatus

The experiments were run in a dimly lit room. The stimuli were presented using a ViSaGe system (Cambridge Research Systems, Rochester, UK) on a gamma-corrected 21-in CRT monitor (Mitsubishi Diamond Pro 2070SB) with a resolution of 1,024 × 768 pixels and a refresh rate of 100 Hz unless stated otherwise. The software used for creating the stimuli and running the experiment was MATLAB 2007b (The MathWorks, Natick, MA). Three buttons of a five-button RB-530 response box (Cedrus, San Pedro, CA) were used. Participants placed their head on a chin rest to stabilize their head. The viewing distance from the screen was 60 cm. The background was gray (56 cd/m^2). Every trial started with the presentation of a black fixation cross in the screen center for 1 s. Then three Gabors were shown for a total duration of 2 s at an eccentricity of 6° (center-to-center from fixation point). The size of the Gabors was ~3.2° (cut-off at 5% contrast) with a spatial frequency of 2 cpd. The orientation of the three Gabors varied independently and randomly from trial to trial. The 50-Hz flicker was created by alternating Gabors with a contrast of 100 and 0% on a CRT with a refresh rate of 100 Hz (see Fig. 1). The 100-Hz flicker was created by presenting Gabors at 50% contrast on every screen refresh. Thus the time-averaged contrast of all Gabors was equal. When a transition from 50- to 100-Hz flicker occurred (discontinuous conditions), the last cue frame before target presentation at 50% contrast and 100 Hz could either be a Gabor of 100% contrast or a Gabor with 0% contrast. In some of the experiments reported in the following text, we tested whether the contrast of the last frame of the flicker cue had an effect on performance. This was not the case and the analyses are not reported for brevity. The target in the RT task (see following text) was an increase or decrease of spatial frequency by 0.14 cpd. The direction of the change in spatial frequency varied randomly from trial to trial.

Recordings of the stimuli were made using a high-speed camera (Hot Shot INT 1280, NAC Image Technology, Simi Valley, CA) at a sample frequency of 500 Hz to verify that the stimuli were programmed correctly and that the perceived flash at the transition between 50- and 100-Hz flicker was perceptual rather than physical. These measurements showed nothing erroneous (e.g., a flash, movement, or increase in luminance) that could be responsible for the consciously perceived transition from 50 to 100 Hz.

Tasks

In *experiments 1* and *6,* we sought to study the perception of flicker. Therefore observers were asked to indicate the location of the flickering stimulus by pressing a spatially corresponding key. Importantly, we asked observers to be as accurate as possible while neglecting response speed. This task is referred to as *perceptual task* because the main dependent variable was accuracy. RTs were not analyzed.

In *experiments 2–5* and *7,* we sought to study the effect of flicker cues on RTs. Observers were asked to indicate the location of a change in spatial frequency or polarity by pressing a spatially corresponding key. Participants were instructed to respond as rapidly as possible while minimizing errors. This task is referred to as *RT task* because the main dependent variable was RT. We nonetheless analyzed choice errors. In sum, all experiments except for *experiment 8* employed a spatial, three-alternative forced-choice (3 AFC) procedure. The perceptual and RT task differed with respect to the feature that had to be localized (flicker vs. spatial frequency change) and the response requirements (unspeeded vs. speeded responses).

Experiment 1: perceptual task with continuous and discontinuous flicker

Eighteen naïve undergraduate students (12 female) participated after performing in another experimental task for 30 min (i.e., they were completely light-adapted). In one block of 288 trials, one of the three Gabors flickered at a frequency of 50 Hz for 1 s, followed by 1 s of 100-Hz flicker. In another block of 288 trials, one Gabor flickered continuously at a frequency of 50 Hz for 2 s. In both conditions, the two remaining Gabors were continuously presented at 100 Hz. The order of the two conditions (continuous vs. discontinuous flicker) was counterbalanced across participants.

We provided feedback about participants' localization performance: a sound was presented when participants gave the wrong response and the percentage of correct responses in the preceding block of trials was displayed during five 20-s breaks per condition. The feedback was given to motivate participants. They were told to try to perform above chance level (33%). The first 48 trials were considered as practice trials and were excluded from analysis.

Experiment 2: RT task with continuous and discontinuous flicker

Twelve naïve students (8 female) participated. A change in spatial frequency of 0.14 cpd occurred 1 s after Gabor onset in one of the three Gabors (i.e., the target). Fifty-hertz flicker was used as a spatial cue. In 50% of the trials, the flicker was presented in the same Gabor as the change in spatial frequency (congruent condition). In the other 50% of trials, the flicker was presented in a Gabor different from the one with the change in spatial frequency (incongruent condition). In one block of 144 trials, the cued Gabor flickered for 1 s until target onset (discontinuous flicker). In another block of 144 trials, the cued Gabor flickered during the entire stimulus presentation of 2 s (continuous flicker). This means that when the cue coincided with the target, the target continued to flicker at 50 Hz. The order of the two conditions (continuous vs. discontinuous flicker) was counterbalanced across participants. A warning sound was presented when participants made an incorrect response. A text message was shown to signal anticipations and failures to respond in time.

Experiment 3: RT task with subtle and salient targets

Fifteen naïve students (13 female) participated. In one block of 144 trials, the target was a subtle change in spatial frequency of 0.14 cpd. In another block of 144 trials, the target was a salient change in polarity (i.e., the phase of the sine wave was shifted by 180°). The order of the two conditions (subtle target vs. salient target) was counterbalanced across participants. As in *experiment 2,* the target change was preceded by a 50-Hz flicker cue in one of the Gabors that was either congruent or incongruent with the target location. The 50-Hz flicker always ended with target onset (i.e., discontinuous flicker).

Experiment 4: RT task with salient cue and target

Seven naive students (6 female) participated. In 192 trials, the target was a salient change in polarity, occurring after 1 s. The 50-Hz flicker cue was not used in this experiment. Instead the cue was a salient white bar (1.8° wide and 0.2° high, 50-ms duration) appearing 2.5° above one of the three Gabors (center-to-center) at the same time as the change in polarity. This particular timing of the white bar was chosen because it resembled the timing of the transition flash.

Experiment 5: RT task with different cue presentation times

Eight naïve students (7 female) participated. During 192 trials the flicker cue appeared 900 ms after Gabor onset and was present for 100 ms. In another block of 192 trials, the flicker cue appeared 600 ms after Gabor onset and was present for 400 ms. The order of the two conditions (100-ms flicker cue vs. 400-ms flicker cue) was counterbalanced across participants. The offset of the flicker cue coincided with the onset of the target.

Experiment 6: perceptual task with flicker at different spatial frequencies

In total, 18 naïve students (16 female) participated. During a block of 216 trials, one of the Gabors initially flickered at 50 Hz for 1 s before it changed to 100 Hz. In another block of 216 trials, one of the Gabors flickered continuously at 50 Hz. Block order was counterbalanced. The spatial frequency of the sine-wave was 0.5, 1, 2, or 4 cpd. The spatial frequency was the same for the three Gabors appearing at the same time but varied randomly between trials. To accommodate the lower spatial frequencies, the Gabor envelopes were enlarged to ~4.2°. A group of 10 participants saw the stimuli at the refresh rate used in the previous experiments (i.e., 100 Hz). For a second group of eight observers, the refresh rate of the monitor was raised to 140 Hz. Thus the flicker cue was at the extreme of the midgamma range (i.e., 70 Hz). The total number of frames was not adjusted such that the display duration decreased from 2 s at 100-Hz refresh rate to 1.4 s at 140 Hz. In either case, the display duration is rather long, and we do not believe that the different presentation time per se would change performance.

Experiment 7: RT task with subliminal flicker

Eight naïve students (8 female) participated. The experiment is a repetition of the continuous flicker condition in *experiment 2* but with a higher screen refresh rate of 140 Hz and a stimulus presentation time of 1.4 instead of 2 s. There were 144 trials in this experiment.

Experiment 8: RT task with subliminal flicker at central fixation

Ten naïve students (7 female) participated. In 144 trials, a single Gabor patch was presented at central fixation. The grating flickered continuously either at 70 or 140 Hz. After 0.7 s, the sine-wave grating changed spatial frequency and participants were asked to rapidly press one of two buttons (2-alternative forced-choice procedure) to indicate whether an expansion or contraction of the grating had occurred.

RESULTS

We calculated median RT and proportion correct for each condition and participant. For the RT task, trials with RTs <100 ms and >1 s as well as erroneous trials were removed before calculating median RTs. Unless noted otherwise, paired, two-tailed *t*-test were run to test for significant differences between conditions. RTs and percentage correct are summarized in Fig. 2. The overall percentage of correct responses in *experiments 2–5* and *7* and *8* was 75, 98, 96, 90, 97, and 94%, respectively.

Experiment 1: perceptual task with continuous and discontinuous flicker

A one-sample *t*-test (2-tailed) showed that participants could localize the discontinuously flickering Gabor with an accuracy of 54% which is significantly better than chance (33%), $t(17) = 5.63$, $P < 0.001$. When the flicker was continuous, performance dropped to 40%, but was still above chance, $t(17) = 2.84$, $P = 0.011$. The percentage of correct responses

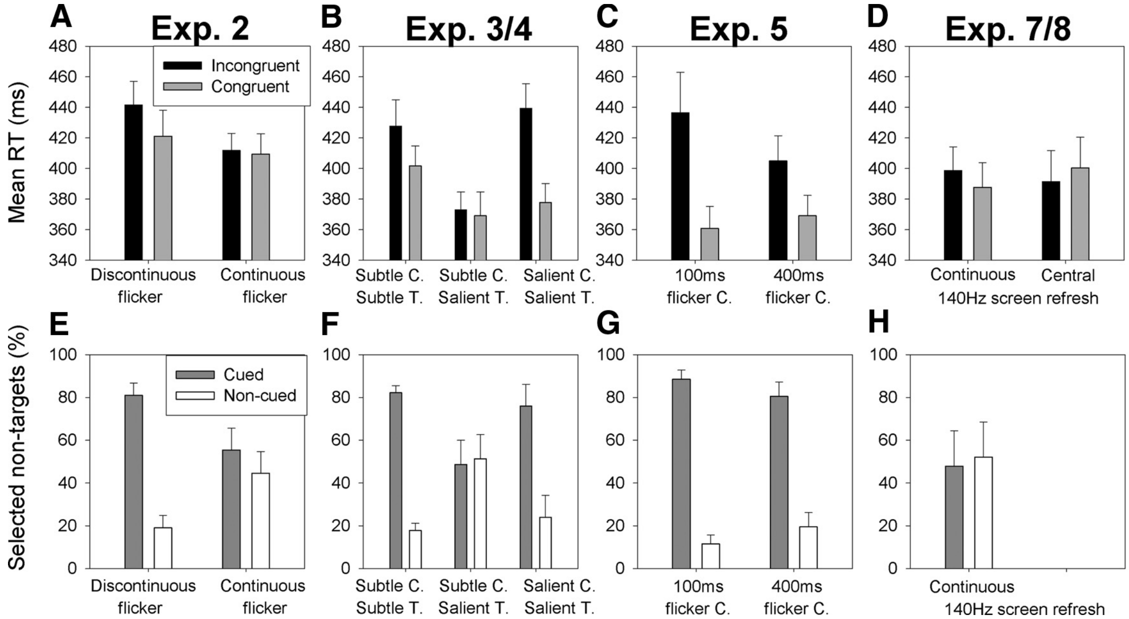

FIG. 2. Results of the reaction time (RT) task in *experiments 2–5* and 7 and *8*. *Top*: mean RTs (based on individual medians). *Bottom*: the respective error patterns in incongruent trials. The proportion of selected nontargets indicates how frequently participants selected the cued (flickering) Gabor or the non-cued Gabor instead of the target in incongruent trials. *A* and *E*: effects of cue-target congruency with discontinuous and continuous flicker in *experiment 2*. *B* and *F*: effects of cue-target congruency with subtle and salient stimuli. In *experiment 3,* a subtle cue (discontinuous flicker) was combined with subtle and salient targets (change in spatial frequency and polarity, respectively). In *experiment 4,* a salient cue (white bar) was combined with a salient target (polarity change). *C* and *G*: effects of cue-target congruency with flicker cues of 100- or 400-ms duration presented right before target onset. *D* and *H*: effects of cue-target congruency with continuous flicker at 70 Hz in *experiment 7* and RTs for a central Gabor flickering at 70 Hz (= congruent) and 140 Hz (= incongruent) in *experiment 8.* The error bars denote the standard error of the mean. C, cue; T, target.

was higher with discontinuous flicker than with continuous flicker (54 vs. 40%), $t(17) = 4.55$, $P < 0.001$. As mentioned in the INTRODUCTION, we believe that an illusory transition flash that is perceived at the transition from 50 to 100 Hz made the discontinuous flicker easier to see. We conclude that Bauer et al.'s procedure in the cue localization task (no feedback, addition of highly dissimilar stimuli, no transition from 50 to 100 Hz) underestimated observers' capacity to localize the discontinuous flicker cue that they subsequently used in their reaction time task.

Experiment 2: RT task with continuous and discontinuous flicker

In the second experiment, we tested whether the cueing effect on RTs depends on the presence of the illusory transition flash. In one block of trials, participants performed the RT task with flicker cues that stopped at target onset (discontinuous flicker), resulting in an illusory transition flash. In another block of trials, participants performed the RT task with flicker cues that continued to flicker after target onset. An interaction between type of flicker (continuous vs. discontinuous) and congruency (congruent vs. incongruent) was confirmed, $F(1,11) = 5.32$, $P = 0.042$. Similar to Bauer et al., we observed a congruency effect of 21 ms with discontinuous flicker, $t(11) = 3.11$, $P = 0.01$. However, no significant congruency effect was observed with continuous flicker (2 ms), $P > 0.5$, which contradicts the hypothesis that the flicker itself attracted attention (see Fig. 2*A*). Rather the results support the idea that the subtle transition flash interfered with the localization of the subtle change in spatial frequency.

When participants failed to respond to the target in the discontinuous flicker condition (see Fig. 2*E*), they selected the cued Gabor more often than the non-cued Gabor (81 vs. 19%), $t(10) = 5.35$, $P < 0.001$, suggesting that observers confused the illusory transition flash with the change in spatial frequency. With continuous flicker, there was no bias to mistake the flicker cue for the target in incongruent trials (55 vs. 45%), $P > 0.6$. This means the illusory transition flash, not the flicker itself, was confused with the subtle change in spatial frequency. Although the flicker was perceived above chance by some participants, this was not enough to cause confusion. Because participants were looking for a change at a certain moment, they were distracted by the illusory transition flash occurring at exactly the same time as the change in spatial frequency. That is, the illusory flash coincided with the searched-for discontinuity and was equally subtle and short-lived, which made the two events easy to confuse.

Experiment 3: RT task with subtle and salient targets

If confusion between the subtle flicker cue and the subtle target change explained the results obtained by Bauer et al. (2009), the cueing effect is expected to disappear when the probability of confusing the two events is reduced. We tested this prediction in *experiment 3* by using a highly salient reversal of polarity as target in addition to the subtle change in spatial frequency.

RTs to the salient target were shorter than RTs to a subtle target (371 vs. 415 ms), $F(1,14) = 16.51$, $P = 0.001$, and congruent cues produced shorter RTs than incongruent cues (385 vs. 400 ms), $F(1,14) = 7.59$, $P = 0.015$. Importantly, the analysis revealed a significant interaction between type of target (salient vs. subtle) and congruency (see Fig. 2*B*), $F(1,14) = 4.71$, $P = 0.048$. Consistent with our prediction, the congruency effect in the RT task disappeared with a salient change in polarity (4 ms), $P > 0.5$, while a cueing effect of 26 ms was present for the subtle change in spatial frequency in the same group of participants, $t(14) = 2.93$, $P = 0.011$. Further, participants did not select the flicker cue more often than the non-flickering Gabor (see Fig. 2*F*) when they failed to respond to the salient target on incongruent trials (49 vs. 51%), $P > 0.9$. In contrast, cue-target confusion was present for the subtle target (82 vs. 18%), $t(14) = 9.6$, $P < 0.001$.

Experiment 4: RT task with salient cue and target

One may object that the absence of the cueing effect with a salient target in the previous experiment was due to a floor effect caused by fast RTs. Therefore another experiment was run in which a more salient cue preceded the salient target. Instead of subtle 50-Hz flicker, a salient white bar appearing above the Gabor served as cue.

The salient cue produced a robust cueing effect of 62 ms on speeded localization of the salient target (see Fig. 2*B*), $t(6) = 5.75$, $P < 0.001$. The error pattern (see Fig. 2*F*) confirms that cue-target confusion was also present (76 vs. 24%), $t(6) = 2.55$, $P = 0.043$. Because the salient cue produced a congruency effect, the absence of cueing effects with a salient target in *experiment 3* cannot be explained by fast RTs (i.e., a floor effect).

Experiment 5: RT task with different cue presentation times

There is one aspect of Bauer et al.'s (2009) data that contradicts our hypothesis. They reported that the cueing effect was absent when the duration of the cue was reduced to 100 ms just before target presentation. That is, there was 100-Hz flicker for 900 ms, then the cue Gabor flickered at 50 Hz for 100 ms and changed back to 100 Hz when the target change occurred. According to our hypothesis, there should be an illusory flash at the transition from 50 to 100 Hz that is confused with the target and a cueing effect should occur. In contrast, Bauer et al. reported that the cueing effect was absent. In *experiment 5,* we ran conditions with cue durations of 400 and 100 ms.

In support of our hypothesis, reliable cueing effects (see Fig. 2*C*) were observed in both the 100-ms (76 ms), $t(7) = 5.2$, $P < 0.001$, and 400-ms condition (36 ms), $t(7) = 5.85$, $P < 0.001$. In addition to the main effect of congruency, $F(1,7) = 42.56$, $P < 0.001$, the significant interaction of congruency and duration showed that the cueing effect was larger with cue durations of 100 than 400 ms, $F(1,7) = 7.59$, $P = 0.028$. Bauer et al. (2009) reported the opposite result, a larger cueing effect with long than with short cues. We cannot offer a good explanation for the discrepancy between Bauer et al.'s and our results. It may be that methodological differences contribute to the discrepancy. Bauer et al. presented four cue durations in random order, whereas we had only two cue durations in separate blocks of trials. Finally, we cannot rule out the possibility of unknown, unstated differences between our settings and Bauer et al.'s.

Note, however, that the observation of cue-target confusion for both cue conditions favors our results: participants selected the flicker cue more often than the non-flickering Gabor when they made a mistake in the incongruent condition (see Fig. 2*G*): 81 versus 19% for the 400 ms flicker cue, $t(7) = 4.56$, $P = 0.003$, and 89 versus 11% for the 100 ms flicker cue, $t(7) = 9.07$, $P < 0.001$.

Experiment 6: perceptual task with flicker at different spatial frequencies

The conclusion of Bauer et al. (2009) that flicker at 50 Hz is subliminal is surprising because it is public knowledge that bright CRT screens running at 50 Hz appear to flicker, particularly in peripheral vision. For most observers, the critical flicker fusion (CFF) frequency is around 70 Hz, but interindividual variation is substantial (Bauer et al. 1983; Jaschinski et al. 1996). However, the CFF frequency in Bauer et al. (2009) may have been lower because they presented stimuli at a rather high spatial frequency of 2 cpd. Bauer et al. (1983) noted that CFF frequencies decrease with decreasing stimulus size and luminance. In fact, they reported that the CFF frequency for a small stimulus of 0.8° diam was <50 Hz. Similarly, the CFF frequency may be lower for high spatial frequencies.

To clarify how flicker perception depends on spatial frequency, we asked participants to indicate the position of a flickering Gabor among three Gabors of equal spatial frequency. Spatial frequency varied from trial to trial between 0.5, 1, 2, and 4 cpd. Further, we varied the type of flicker (continuous, discontinuous) and the refresh rate of the CRT (100 Hz, 140 Hz, between participants). Recall that a refresh rate of 140 Hz results in 70-Hz flicker targets for the perceptual task. We ran a mixed-factor ANOVA (refresh rate × flicker type × spatial frequency) on proportion correct responses (see Fig. 3, *A* and *B*). The between-subject factor refresh rate was significant, $F(1,16) = 33.86$, $P < 0.001$, showing that flicker localization was better with 100-Hz than with 140-Hz refresh rate (68 vs. 49%). Discontinuous flicker was easier to localize than continuous flicker (69 vs. 49%), $F(1,16) = 97.78$, $P < 0.001$; this confirms the better visibility of the illusory transition flash. The effect of flicker type was modulated by refresh rate, $F(1,16) = 24.38$, $P < 0.001$, showing that the difference between discontinuous and continuous flicker was larger at 140-Hz than at 100-Hz refresh rate (difference of 30 vs. 10%). There was an effect of spatial frequency, $F(3,48) = 198.09$, $P < 0.001$, showing that performance decreased with increasing spatial frequency. The effect of spatial frequency parallels the effect of stimulus size in Bauer et al.'s (1983) experiment. Furthermore, the influence of spatial frequency on accuracy was modulated by refresh rate, $F(3,48) = 10.72$, $P < 0.001$, and flicker type, $F(3,48) = 34.44$, $P < 0.001$, and the three-way interaction between all factors was also significant, $F(3,48) = 26.87$, $P < 0.001$. Inspection of Fig. 3 suggests that the latter interactions occur because spatial frequency did not affect performance in a single condition: with continuous flicker at 140-Hz refresh rate, there was no effect of spatial frequency (1-way ANOVA, $P = 0.391$), and performance was at chance level throughout. In all other conditions, spatial frequency had a large effect, *F*'s >53, *P*'s < 0.001, and performance increased from near-chance at high spatial frequencies to almost 100% correct at low spatial frequencies.

These results further consolidate that flicker perception was clearly above chance for the stimuli used by Bauer et al. (2009). Performance at 2 cpd in the present experiment was even better than in *experiment 1* (discontinuous flicker: 58 vs. 54%, continuous flicker: 48 vs. 40%). Performance may have

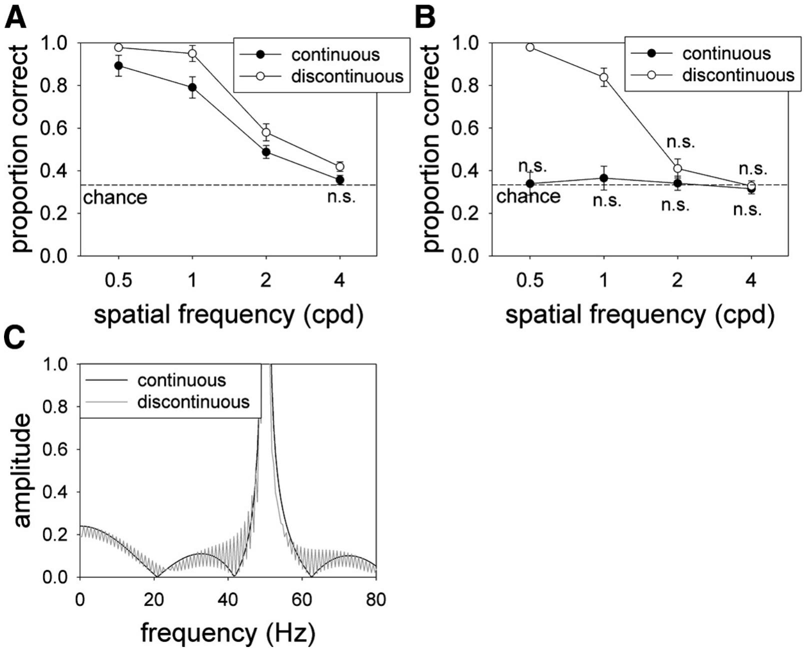

FIG. 3. Results of the perceptual task in *experiment 6* and Fourier analysis. Panels A and B show the proportion of correct responses when observers had to indicate the position of continuous or discontinuous flicker. *A* and *B*: the results as a function of spatial frequency with screen refresh rates of 100 and 140 Hz, respectively. Each mean was compared with chance level (33%) and marked nonsignificant (n.s.) when it failed to reach the Bonferroni-adjusted $P = 0.05/4$. *C*: the Fourier spectra for continuous and discontinuous flicker at a refresh rate of 100 Hz. The 50-Hz flicker ends with 0% contrast. A discrete Fourier transform (MatLab function "fft") was run on a vector in which the cue contrast was specified for each millisecond over 2 s.

improved because the stimuli were larger (4.2 vs. 3.2°) or because clearly visible flicker at low spatial frequencies helped observers to establish a search template. Quite a few participants in *experiment 1* complained that they did not know what to look for. Further, the results show that flicker perception was better with low spatial frequencies. The reason for better perception of flicker at low spatial frequencies may be that cells able to follow high temporal frequencies (magnocellular cells) are most sensitive to low spatial frequencies (e.g., Dreher et al. 1976; Kulikowski and Tolhurst 1973; Wiesel and Hubel 1966). Finally, continuous flicker at 70 Hz was subliminal for all spatial frequencies tested. Therefore we repeated the RT task of *experiment 2* with continuous flicker at 70 Hz in *experiment 7*.

Experiment 7: RT task with subliminal flicker

Our findings in *experiment 3* and *4* suggest that Bauer et al.'s (2009) results are partially accounted for by search strategies. When observers look for a subtle change, they are distracted by a subtle change occurring elsewhere at the same time. When looking for a salient change, the same subtle change does not disturb performance. Similarly, Bauer et al. noted that above-threshold flicker cues (25 and 30 Hz) do not affect RTs. This suggests that observers may ignore visual events that do not match the searched-for event, a phenomenon that is known as contingent attentional capture (Folk et al. 1992). Presumably, voluntary exclusion of irrelevant events depends on conscious perception. Therefore we explored whether truly subliminal flicker attracts attention as originally proposed by Bauer et al.

Experiment 6 has established that a 2 cpd Gabor flickering at 70 Hz is perceptually indistinguishable from a 2-cpd Gabor flickering at 140 Hz. Therefore participants are expected to be unable to ignore 70-Hz flicker voluntarily when searching for the target in the RT task. Voluntary neglecting presupposes conscious perception of the stimuli. In this experiment, we repeated the RT task with continuous flicker. Recall that we observed no cueing effects with continuous 50-Hz flicker cues in *experiment 2*. In the present experiment with 70-Hz flicker, RTs were slightly faster (see Fig. 2*D*) with congruent than with incongruent cues (388 vs. 399 ms), $t(9) = 3.96$, $P = 0.005$. There was no significant tendency to select the cued Gabor more often than the uncued Gabor in incongruent trials (see Fig. 2*H*) when subjects made an error (48 vs. 52%), $P > 0.9$. That is, there was no tendency to confuse the flickering Gabor with the target. At first sight, the present results support the proposal of Bauer et al. (2009) that subliminal flicker in the gamma band may automatically attract attention. However, the authors reported cueing effects that were about twice as large as the present cueing effect (20–25 vs. 11 ms). Recall that Bauer et al. presented suprathreshold discontinuous flicker (i.e., a condition that we find produces an illusory transition flash), whereas in the present experiment, we presented subliminal continuous flicker.

A possible interpretation of the discrepancy is that more than one factor contributes to the cueing effects reported by Bauer et al. First, confusion between cue and target may contribute when an illusory transition flash occurs (cf. the present *experiments 2–5*). Second, the flicker may cause neural entrainment and gamma-band synchronization as originally proposed by Bauer et al. Because the latter effect is small, it may be occasionally absent (cf. *experiment 2*) or masked by search strategies. However, the conclusion that subliminal flicker may automatically attract attention rests on the assumption that the 70- and 140-Hz flicker are perceptually equivalent in all behavioral tasks. Conscious report is only one of them. It has been repeatedly shown that perceptual report may dissociate from motor performance (e.g., Klotz and Neumann 1999; Vorberg et al. 2003). Therefore it is possible that subliminal differences cause a behavioral effect in the absence of attentional selection.

Experiment 8: RT task with subliminal flicker at central fixation

In this final experiment, we sought to clarify whether stimuli flickering at 70 and 140 Hz produce equivalent RTs when there is no need to select the stimulus among distractors. Remember that the argument of Bauer et al. (2009) was that flicker in the midgamma band attracted attention and thereby enhanced visual processing. In the present experiment, we presented a single Gabor at central fixation. Because there were no distractors and central fixation is the natural locus of attention, we consider that selective attention is not involved in the task. Because it was not possible to ask observers to localize the change in spatial frequency, we asked them to indicate the direction of the change (expansion or contraction) by pressing one of two designated keys. RTs to stimuli flickering at 70 Hz were 9 ms slower (see Fig. 2*D*) than RTs to stimuli flickering at 140 Hz (400 vs. 392 ms), $t(9) = 2.6$, $P = 0.029$, showing that RTs differed in the absence of attentional selection. Accuracy did not differ between 70- and 140-Hz flicker (0.94 vs. 0.94), $P > 0.8$.

At first, it is surprising to see that the 70-Hz stimulus that corresponds to the target in the congruent condition in the previous RT task was responded to more slowly than the 140-Hz stimulus that corresponds to the target in the incongruent condition. However, there are numerous differences that may explain the unexpected result. Most importantly, the task was different. In the previous experiment, the task was a localization task, whereas it was a discrimination task in the current experiment. Because task demands were different, the same stimulus characteristics may result in better or worse performance. Further, higher spatial resolution, but worse flicker perception (Bauer et al. 1983) in the fovea may have contributed (in unknown ways) to the result. Also there might remain a small energy difference between 70- and 140-Hz flicker despite the low-pass filtering properties of the visual system. The 140-Hz flicker has two screen refreshes for every refresh of the 70-Hz flicker that may result in higher energy. The difference is probably too small to be consciously noticed, but it may explain the small RT advantage for 140-Hz flicker in *experiment 8*. In addition, the 70-Hz stimulus being less "intense" than the simultaneously present 140-Hz stimuli could attract attention to it (cf. *experiment 7*).

While all our interpretations of the RT difference remain speculative, the important point to retain is that RTs to stimuli flickering at 70 and 140 Hz differ in the absence of selection by attention. Thus the small effect of cue-target congruency that we observed in the previous experiment cannot be unequivocally attributed to attentional selection by neural entrainment. While we do not fully understand the underlying mechanisms, the results show that subliminal differences between flicker of 70 and 140 Hz lead to changes in RTs.

DISCUSSION

Our results show that previously reported cueing effects by flicker in the midgamma band (Bauer et al. 2009) cannot be unequivocally attributed to automatic attraction of attention through neural synchronization. Instead we propose that the observed cueing effects result in large part from the perceptual impression of a flash that occurs at the transition from 50- to 100-Hz flicker. Observers confuse the illusory transition flash with the target (a subtle change in spatial frequency) because the two events resemble each other. Recall that the flicker cue in Bauer et al. (2009) always changed from 50 to 100 Hz at the time of target onset. In contrast, we also ran conditions in which we presented the 50-Hz flicker continuously until the end of the trial and found no cueing effect. Further support for the claim that the illusory transition flash in the discontinuous flicker condition causes cue-target confusion comes from the error patterns in incongruent trials. Moreover, when participants were searching for a target that did not resemble the illusory transition flash, the flicker cues failed to produce cueing effects. Finally, small cueing effects did occur when the flicker cue was truly subliminal at a refresh rate of 140 Hz. However, these effects were very small and may be accounted for by perceptual differences that affect RTs but not perceptual report. In other words, we do not believe that the effects are due to attentional mechanisms.

The flash perceived at the transition from 50- to 100-Hz flicker has—to our knowledge—not been studied in the literature before. However, Baccino, Jaschinski, and Bussolon (2001) made an observation that resembles our illusory transition flash. They noted that when they switched an analogue light source from continuous to 50-Hz flicker, the transition was visible despite the time-averaged contrast being equal. Also they found that switching from continuous light to light flickering at 50 Hz at target onset slowed down saccades, which is reminiscent of the remote distractor effect (e.g., Born and Kerzel 2009; Walker et al. 1997). In passing, they note that "any such switch was visible, even with flicker pulses of 100 Hz, since it also includes frequency components well below CFF, as predicted by Fourier analysis" (Baccino et al. 2001; p. 3913). Therefore we ran a Fourier analysis on a vector that specified cue contrast for every millisecond of the entire display duration. The results are presented for 50-Hz flicker in Fig. 3*C*. Possibly, the illusory flash at the transition between 50- and 100-Hz flicker is accounted for by the increased amplitude ~40 Hz that is visible in the graph.

A complementary hypothesis focuses on the temporal characteristics of visual processing. Previous research suggest the visual system blurs information over a time interval of ≥20 ms (Holcombe 2009). An integration interval <20 ms is plausible because flicker of 50 Hz was difficult but not impossible to perceive. The continuous 70-Hz flicker was clearly subliminal, suggesting that the integration interval was >14 ms. Thus the size of the integration interval is somewhere between 14 and 20 ms. When subsequent Gabors of 10 ms each alternate between 100 and 0%, the perceived mean contrast will be close to 50% even when the integration interval is slightly <20 ms. At the transition from 50- to 100-Hz flicker, however, the mean contrast in the integration interval differs strongly from 50%. This is the case, irrespective of whether the last Gabor of the 50-Hz flicker is presented at 100 or 0% contrast. At a refresh rate of 140 Hz, the deviation from the average contrast of 50% at the transition will be smaller than with a refresh rate of 100 Hz, which is confirmed by worse perception of discontinuous flicker in the 140-Hz condition of *experiment 6*. While the explanation of Baccino et al. (2001) focused on the physical properties of the stimulus, our integration interval account emphasizes the role of the temporal characteristics of sensory processing. Therefore the two hypotheses do not exclude one another.

In sum, the present study casts doubt on the usefulness of visual flicker to study the behavioral consequences of neural gamma-band synchronization. First, some of the results reported by Bauer et al. (2009) are due to a largely unknown psychophysical phenomenon, an illusory flash occurring at the transition between 50- and 100-Hz flicker. Second, cueing effects that cannot be attributed to the illusory transition flash are very small and may result from subliminal effects on RTs in the absence of visual selective attention.

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