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This impression, however, is challenged by a growing number of studies suggesting that the spotlight "blinks" rhythmically, leading to alternating cycles of improved and impaired behavioral performance at the cued and uncued locations (Dugué, Roberts, & Carrasco, 2016; Fiebelkorn & Kastner, 2019; Landau & Fries, 2012), even when sustained attention is promoted at the cued location (Fiebelkorn, Saalmann, & Kastner, 2013). In these studies, a visual stimulus is first presented as a time reference, by which the attentional cycle could be reset and aligned across each trial (VanRullen, 2016). Importantly, the SOA between the first stimulus (a spatial cue) and the subsequent target is manipulated with a fine temporal resolution (e.g., 50 Hz given the SOA varying in steps of 20 ms) such that the behavioral performance at multiple phases within an attentional cycle couldessubs

were filtered, and the reward modulation based on this low-frequency data was assessed. This was to replicate the findings in previous studies where responses to the target were sampled discretely and sparsely. Second, time-frequency analysis was applied to the RT time courses. With this analysis, spectrotemporal changes in RT time courses were examined. This was to examine whether the relative alpha power between the cue valid and cue invalid conditions was periodically changed (Song et al., 2014) and how the alpha power difference was modulated by reward.

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Participants

Twenty-two university students participated in the experiment (nine males, all right-handed, 18 23 years of age, mean = 20.4 years). All participants had normal or corrected-to-normal visual acuity, and none of them reported color-blindness or weakness. Participants received 50 RMB (about US$7) for participation and could earn extra 0 20 RMB, depending on their performance in the task. This study was performed in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the School of Psychological and Cognitive Sciences, Peking University.

Design and procedure

Participants sat in front of a CRT monitor (refresh rate = 100 Hz) in a dimly lit room, with their heads stabilized in a chin rest. The eye-to-monitor distance was fixed at 70 cm. Responses were obtained through a standard keyboard by pressing "F" and "'J" keys. Three placeholders with black frames (each placeholder with a visual angle of $2° × 2°$) were presented against a white screen throughout each trial. The boxes were localized side by side, with equal distances between the adjacent two boxes ($4°$ between the centers of the boxes). Participants were required to maintain eye fixation on the central box without making eye movements.

In each trial, after a varied interval of 800 1,200 ms, a cue was presented inside either the left or right box for 100 ms. This cue was either a red or green square that filled in the box. The color of the cue signaled a potentially high or low reward, with the association between the color (red vs. green) and the reward level (high vs. low) counterbalanced across individuals. After another varied interval of 100 1,000 ms, a target letter "X" or "O" ($1.3° × 1.3°$) was presented inside the left or right box for 150 ms. That is, the stimulus onset asynchronies (SOAs) between the cue and the target were varied from 200 ms to 1,100 ms. The target was presented in the same box as the cue (cue valid condition) or the opposite box of the cue (cue invalid condition) with equal probability. Thus, the location of the cue was uninformative of the location of the target. Participants were asked to identify the target by pressing "F" or "J" on the keyboard with the left and the right index finger, respectively. The mapping between the letter identity ("X" vs. "O"

given. In a high-reward trial, a correct and fast response would result in the gain of 10 points; in a low-reward trial, a correct and fast response would result in the gain of 1 point. In trials where the response was incorrect or slow, no reward would be obtained. Participants were informed that the points gained in each trial would be accumulated during the experiment; at the end of the experiment, the total points would be proportionally exchanged to money in addition to the basic payment.

The crucial manipulation was the fine temporal assessment of the behavioral performance on target discrimination (Dugué et al., 2016; Landau & Fries, 2012). To achieve this temporal resolution, the SOA between the cue and the target in a trial was chosen from one of 46 values from 200 ms to 1,100 ms in steps of 20 ms after cue onset, corresponding to a sampling rate of 50 Hz. There were 440 trials for each of the four experiment conditions: high-reward, valid; high-reward, invalid; low-reward, valid; low-reward, invalid. In each condition, the number of trials with the SOA of 200 ms was 10 times (i.e., 80 trials) more than the number of trials with longer SOAs (i.e., eight trials for each of the other 45 SOAs), to achieve a more prominent effect of cue resetting. This was carried out in accordance with a previous study (Fiebelkorn et al., 2011), which showed that the deployment of anticipatory attention to the cue (high probability of target appearance immediately after the cue) could enhance the cue resetting effect (more prominent behavioral oscillation effect than equiprobable target appearance). The four conditions were pseudorandomly distributed in 1,760 trials, and were then divided into 20 blocks with equal length. At the end of each block, the accumulated points thus far were presented on the screen. There were self-paced breaks between blocks. The trial sequences were different for different participants.

Data analyses

Behavioral data were analyzed using MATLAB, in conjunction with the EEGLAB toolbox and wavelet toolbox. For each participant, omissions, trials with RTs lower than 200 ms, and

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The main purpose of our study was to investigate the modu-
latory effect of reward on the rhythmic sampling of spatial
attention. The slow (0

pair of phase-power frequency. The observed PPLV was compared with the distribution of PPLVs under the null hypothesis by subtracting the mean and divided by the standard deviation. This created a normalized Z value of PPLV ($PPLV_z$) for each participant and each pair of frequencies. For group-level statistical analysis, a one-sample t test was applied for PPLVz > 0. False discovery rate (FDR) correction was applied for multiple comparisons (Benjamini & Hochberg, 1995).

The overall response accuracy was high, with correct percentage mean (± SEM) equaling to 97.27 (± 0.39). Only a small number of trials (percentage mean ± SEM: high-reward valid,

1 Mean reaction times (ms) and stand deviations across participants as a function of cue validity and cue-to-target SOAs for the high-reward and low-reward conditions

	High reward		Low reward	
	Valid	Invalid	Valid	Invalid
SOA				
Short (200 280 ms)	391 ± 63	404 ± 77	397 ± 69	401 ± 70
Long (480 1,080 ms)	394 ± 78	381 ± 73	397 ± 77	391 ± 75

reward condition (−0.106) than in the low-reward condition (−0.045), $t(1, 21) = −4.81$, $p < .001$, while the low-pass RTs at the cued position was not influenced by the level of reward (lowpass RTs: high reward, −0.003; low reward, 0.013), $t(1, 21) = −0.89$, $p = .383$. The same pattern was observed on the raw (i.e., unnormalized) RTs (see Table 1).

Periodic alpha power inhibition in the cue-valid condition relative to the cue-invalid condition

After being subtracted (0 2 Hz filtered) the slow-trend signals, the remaining RT time courses (see Fig. 3a) were analyzed using time-frequency analysis (see Material and Method section). The alpha powers for each of the four conditions (i.e., high-reward, valid; high-reward invalid; low-reward, valid; low-reward, invalid) showed periodically changing patterns (see Fig. 3b; similar patterns were observed on the raw RTs; see Supplemental Fig. S4). Further analyses showed that the alpha (8 12 Hz) power for each of the four conditions fluctuated in a delta/low-theta frequency (2 3 Hz; see Fig. 4, middle, FFT analysis, $p < .05$ across frequency corrected). For the low-reward condition, the low-theta (2 3 Hz) phases of the alpha power between the valid and invalid conditions showed a fixed relationship (see Fig. 4, bottom right, Rayleigh test, $n = 22$, $p = .071$), with the phase

. 3 Detrended RT time courses and time-frequency power profiles. Detrended RT time courses and time-frequency power profiles as a function of SOA (200 1,100 ms) and frequency (1 25 Hz). For easy illustration, the SOAs are presented in seconds. **a** Grand average (n = 22) of detrended RT time courses for high-reward (left) and low-reward (right) conditions. The shadows denote ±1 SEM. **b** Grand average of (n = 22) time-frequency power for valid (left) and invalid (right) conditions when the spatial cue associated with a high reward (top) or a low reward (bottom). (Color figure online)
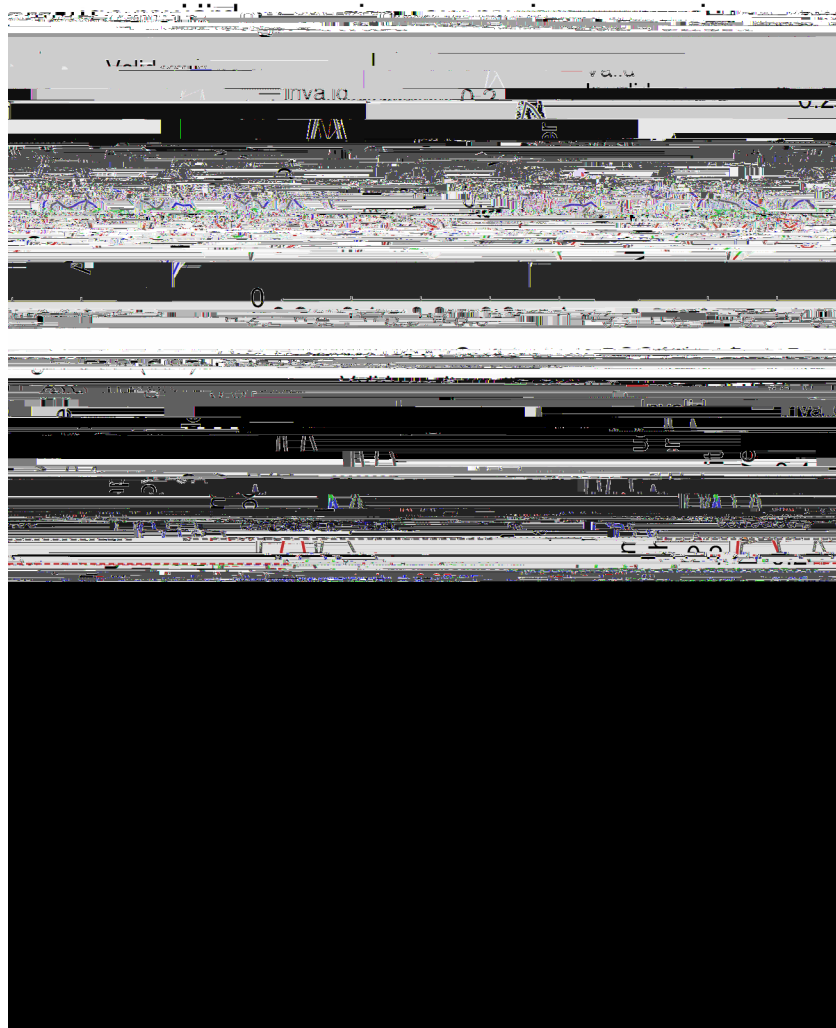
.4 Spectrum amplitude and 2 3 Hz phase relationship of alpha power time courses. For easy illustration, the SOAs are presented in seconds. Top: Alpha power time course. The alpha powers are shown as a function of cue-to-target SOAs for each condition. The shadows denote ±1 SEM.

differences (valid vs. invalid) across participants clustered around a mean of 126°. Such a relationship was not found in the high-reward condition (see Fig. 4, bottom right, Rayleigh test, n = 22, p = .401).

For both the high-reward and low-reward conditions, the power response profiles showed a stronger alpha pattern in the invalid condition than in the valid condition (permutation test, corrected p < .05; see Fig. 5a). FFT analysis on the difference of alpha power between the valid and invalid conditions also showed significant low-theta (2 3 Hz) band fluctuation in both the high-reward and low-reward conditions (permutation test, corrected p < .05; see Fig. 5c). These results suggested that after attention on the two peripheral boxes had been reset by the cue,

the RT time courses at the cued location underwent pulsed alpha-band fluctuations relative to those at the uncued location in a delta/low-theta (2 3 Hz) rhythm for both reward conditions.

We also investigated the time-frequency power difference between the high-reward and low-reward conditions for the valid and invalid conditions separately. For the valid condition, stronger alpha power was observed in the low-reward condition than the high-reward condition during the short cue-to-target SOAs (200 300 ms), while stronger theta power was observed in the high-reward condition than the low-reward condition during the long cue-to-target SOAs (700 1,100 ms) (permutation test, corrected p < .05; see Fig. 6, left). For the invalid condition, stronger alpha power was observed in the
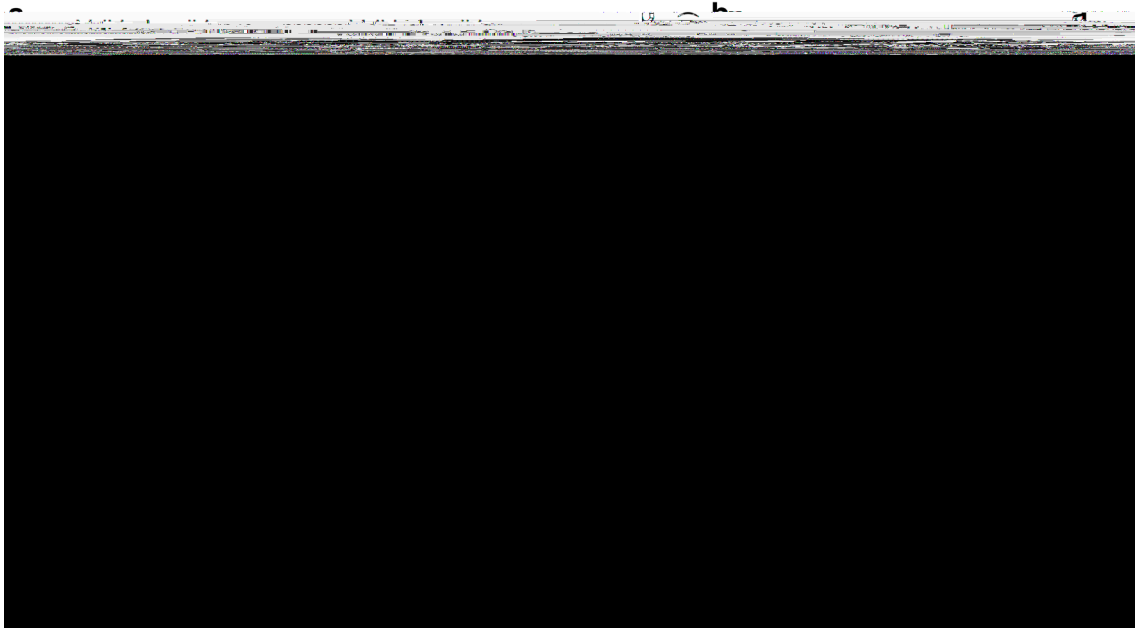
. 5

low-reward condition than the high-reward condition (permutation test, corrected p < .05; Fig. 6, right), which showed a periodically changing pattern.

Periodic alpha pulses emerged earlier under higher reward

The correlation coefficients of alpha power (valid invalid) time courses between the high-reward and low-reward conditions are shown in Fig. 7a as a function of shifted lags. The results showed that after approximate 120 ms or 420 ms forward shifting, the profiles of alpha power (valid invalid) in the low-reward condition showed the largest positive correlations with that in the high-reward condition (permutation test, p < .05, corrected; see Fig. 7a). These results suggested that after forward shifting of 120 ms or 420 ms, the alpha power profile in the low-reward condition was most similar to the alpha power profile in the high-reward condition. Further analysis showed that the significant correlation after shifting alpha power profiles was not driven by extreme values from a single participant (jackknife method; see Fig. 7a, right). This finding suggested that the fluctuating alpha power pattern emerged 120-ms earlier in the high-reward condition than that in the low-reward conditions. An alternative explanation is that the observed pattern was due to a phase difference.

However, the low-theta phase difference between the high-reward and low-reward conditions was not observed in alpha power (valid invalid) time courses (see Fig. 7c, Rayleigh test, n = 22, p = .365). Furthermore, consistent with the fluctuation of alpha power (valid invalid) time courses with a low-theta band frequency, the correlation coefficients of alpha power (valid invalid) time courses between the high-reward condition and low-reward condition also showed periodic fluctuation with a low-theta band frequency (3 Hz, Fig. 7B, FFT analysis, permutation test, p < .05, cross-frequency corrected).

Results of the time-frequency analysis on the alpha power profiles (valid invalid) showed that the alpha fluctuations manifested with a low-theta frequency (see Fig. 8a). The low-theta (2 4 Hz) power of alpha power difference between the valid and invalid conditions was larger in the high-reward than in the low-reward conditions during the SOA of 200 400 ms, and this pattern was reversed during the SOA of 500 700 ms (see Fig. 8b). These findings suggested that the theta modulations on the alpha power difference emerged earlier for the high-reward condition than for the low-reward condition, which was consistent with the results of cross-correlation analysis.

To explore the relationship between different frequency components, power-phase locking analysis was applied to

the RT time courses across both reward and cue validity conditions. Results showed that the alpha power was phase-locked to the phase of a delta/low theta (1 3 Hz; one-sample t test, n = 22, FDR corrected; see Fig. 8c). The power-phase locking relationship showed no significant difference between the high-reward and low-reward conditions (paired t test, n = 22, FDR corrected).

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In this study, using the classical spatial cuing paradigm and with a dense distribution of SOAs between the cue and the
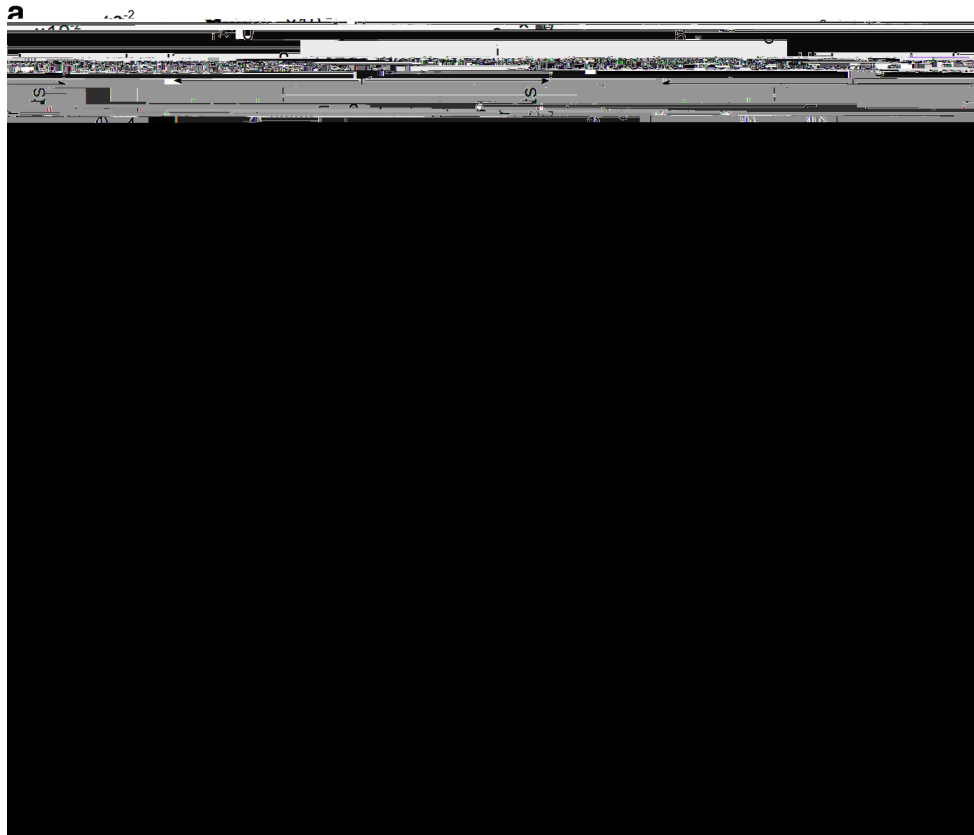
. 7 Results of correlation coefficients. **a** Correlation coefficients with different shifted lags. Correlation coefficients of alpha power profiles (valid invalid) as a function of shifted lags between the high-reward and low-reward conditions are shown. For easy illustration, the shifted lags are presented in seconds. Left: Correlation coefficients for the grand average of alpha power difference (n = 22); the gray horizontal dotted line shows the critical correlation coefficient corresponding to the corrected p

pulsed alpha inhibitions in spatial attentional sampling. Many studies showed that the phase of alpha band activities in the cortex could predict perceptual performance (Busch et al., 2009; Dugué et al., 2011; Harris et al., 2018; Jensen et al., 2014; Sherman et al., 2016). The alpha pulses in the RT time courses could be underscored by the alpha oscillation in the cortex and may represent similar cognitive processes reflected by the alpha band neural activity in the cortex (Song et al., 2014). As the alpha-band activity has been linked to inhibitory functions during attentional processes in many studies (Händel et al., 2011; Helfrich et al., 2017; Kizuk & Mathewson, 2017; Klimesch et al., 2007; Marshall et al., 2018; Thut, 2006; van Diepen et al., 2019), here we suggest that the lower alpha power (alpha inhibition) at the cued location than the uncued location represents enhanced attentional sampling at the cued location. The alpha inhibition that fluctuated in a low-theta frequency may indicate that the

attentional states at the cued location fluctuates in a low-theta frequency, which is consistent with many psychophysics studies showing the dominance of theta in the rhythmic nature of spatial attention (Dugué et al., 2016; Fiebelkorn et al., 2013; Huang, Chen, & Luo, 2015; Landau & Fries, 2012; Song et al., 2014). Taken together, these findings suggest that the rhythmic sampling of spatial attention may be implemented by the periodically fluctuated (2 3 Hz) alpha inhibition.

One might argue that the rhythmic behavioral performance observed here was due to microsaccades, the small involuntary fixational eye movements that have been linked to theta-band neural activities during visual perception (Bosman, Womelsdorf, Desimone, & Fries, 2009; Chen, Ignashchenkova, Thier, & Hafed, 2015). However, using paradigms similar to the present one, recent studies showed that the link between neural oscillations and behavioral performance persists even after the removal of trials with

microsaccades during the cue target delay (Fiebelkorn et al., 2018; Landau, Schreyer, Van Pelt, & Fries, 2015; Spyropoulos et al., 2018), indicating that the periodically fluctuated (2

Kamarajan et al., 2008; Shankman, Sarapas, & Klein, 2011; Wang et al., 2019; Yang, Jacobson, & Burwell, 2017). We propose that as the time-spectral pattern (alpha