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# The timing and temporal patterns of eye blinking are dynamically modulated by attention

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### ARTICLE INFO

#### Article history:

Available online 9 August 2012

#### PsychINFO classification:

2330

#### Keywords:

Spontaneous eye blinking

Attention

Suppression

Facilitation

1/f Scaling

### ABSTRACT

A number of human behaviors and movements show self-similar temporal patterns in their occurrence over time. Human walking, finger tapping and heartbeat intervals have fluctuations that are statistically similar at multiple time scales. However, whether eye blinking, which is a unique human behavior that occurs spontaneously, embeds a similar temporal structure within other types of movements is largely unknown. In this study, we used attention-requiring tasks to assess how the temporal pattern of eye blinking is altered in both the second and sub-second time scales. Our results showed that eyeblink activity was more suppressed as the task difficulty level increased and was facilitated immediately after exposure to auditory stimuli, which were presented for 6 to 14 s. Moreover, similar transient suppressive and facilitative patterns were observed in the response period, which lasted for less than one second. Furthermore, we found that spontaneous eye blinking intervals fluctuated according to an 1/f scaling property, which is widely observed in various human movements. These results suggest that the dynamics of eye blinking under specific cognitive tasks exhibit a similar temporal structure at multiple time scales.

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## 1. Introduction

Many studies have revealed that a number of human movements exhibit variability and self-organized criticality in their occurrence over time (Diniz et al., 2010). The heartbeats of healthy subjects show

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scale-invariant properties in their interbeat intervals (Peng et al., 1993), and the stride interval of human walking has a self-similar pattern on multiple timescales (Delignières & Torre, 2009; Hausdorff et al., 1996). Similar results have also been found in behavioral processes during cognitive tasks. A time-series of errors during the replication of given target trials exhibited an  $1/f$  noise, which is a ubiquitous phenomenon in diverse scientific domains (Gilden, Thornton, & Mallon, 1995). The reaction times observed during a mental rotation task (Gilden, 2001) and the reaction times observed in response to simple visual stimuli also demonstrated an  $1/f$  noise (Van Orden, Holden, & Turvey, 2003). These findings are thought to be related to the formation of representations during cognitive processes (Gilden, 2001).

Although a large number of studies have found that there are scale-invariant, self-organizing properties in human movements and cognitive processes, the temporal structures within the dynamics of spontaneous eye blinking, which is a unique human behavior that occurs regularly, are largely unknown. In human adults, the mean interval of eye blinking is approximately 3 to 5 s, which is much more frequent than the time required to maintain proper tear film thickness (Zametkin, Stevens, & Pittman, 1979). In contrast, infants younger than two months of age demonstrated an extremely long eye blinking interval (approximately 85 s; Ponder, 1927), which is much longer than the average tear breakup time observed in infants (approximately 32 s; Isenberg, Del Signore, Chen, Wei, & Guillon, 1999). The discrepancy between eye blinking rates and the prevention of corneal dryness suggests that there are other factors that affect the occurrence of spontaneous eye blinking in addition to than simply the prevention of eye dryness.

Previous studies have found that various cognitive tasks or behavioral states lead to substantial effects on the eye blinking rate (Bacher & Smotherman, 2004; Cramon von & Schuri, 1980; Doughty, 2001; Holland & Tarlow, 1975; Irwin & Thomas, 2010). In adults, the mean eye blinking rate increases during speaking (Cramon von & Schuri, 1980), casual conversation (Bentivoglio et al., 1997), and memorization (de Jong & Merckelbach, 1990) and in angry or excited states (Ponder, 1927). In contrast, the eye blinking rate decreases during sustained visual tracking (de Jong & Merckelbach, 1990), during the recollection of numbers in a working memory task, and while daydreaming (Holland & Tarlow, 1975). An investigation of the temporal eyeblink distribution during various cognitive tasks demonstrated that eyeblinks are correlated with the cognitive load of the stimuli in each task (Fukuda, 1994, 2001; Ichikawa & Ohira, 2004; Ohira, 1995; Siegle, Ichikawa, & Steinhauer, 2008). Eyeblinks are facilitated after discrimination tasks (Fukuda, 1994), after visual and auditory Stroop tests (Oh, Han, Peterson, & Jeong, 2012; Siegle et al., 2008), and near the end of a line during reading (Orchard & Stern, 1991).

Although it is well established that the eye blinking rate changes under various cognitive conditions, the temporal structure embedded in its occurrence is largely unknown. If eye blinking dynamics share similar properties with other human movements, then we hypothesize that eye blinking might have a similar temporal structure at multiple time scales or fluctuate in an  $1/f$  scaling relationship. Thus, we aimed to study the temporal dynamics of eye blinking under the following two considerations. First, we used an auditory task and response paradigm to investigate how the temporal pattern of eye blinking varies at both the second and sub-second time scales. Second, we performed a spectral analysis on a time series of eye blinking interval data to determine which scaling properties are embedded.

To induce similar cognitive conditions in the second and sub-second time scales, we utilized an auditory attentional task that requires internal counting of perceived tones at the second time scale (6 to 14 s) and utilized a task-relevant auditory cue that requires a rapid response at the sub-second time scale (<500 ms). Because attention is a crucial factor that affects eye blinking rate (Bacher & Smotherman, 2004; Holland & Tarlow, 1975) and task-relevant sensory cues transiently attract attention (Folk, Remington, & Johnston, 1992; Fries, 2001), attention might play a crucial role at both time scales.

## 2. Methods

### 2.1. Participants

Thirty-four subjects (M:F = 18:16) aged 19–28 years participated in this study. Subjects who used contact lenses or suffered from eye dryness were excluded from the study. None of the subjects had previously participated in electroencephalogram (EEG) or electrooculogram (EOG) recording

experiments. To prevent the subjects from being aware that eyeblink timing and frequency were being measured, the subjects were informed before the experiment that the aim of the study was to obtain EEG recordings. When questioned at the end of the experiment, no subject acknowledged an awareness or suspicion that eyeblinks were recorded during the experiment. All subjects provided written, informed consent for the study, which was approved by the Institutional Review Board of the Korea Advanced Institute of Science and Technology (KAIST).

## 2.2. Auditory tone-counting task

The task was designed to have three successive and distinct time periods: the stimulus period, gap period, and response period (Fig. 1A). In the stimulus period, a subject was instructed to listen to a series of tones with different pitches that lasted for 6 to 14 s and asked to mentally count the total number of tones. The tone stimuli consisted of a series of continuous piano tones within the two-octave pitch range of C major. A series of tones were presented at a frequency of 0.5 ~ 1 tone/s for the easy task condition, 2 ~ 3 tones/s for the intermediate task condition, and 4 ~ 5 tones/s for the difficult task condition. Tones with different pitches were presented as a rhythmic pattern of increasing and decreasing pitch or a scattered pattern so that the subjects could not be correct without employing accurate internal counting.

The gap period was inserted to help to experimentally dissociate the influences of the stimulus offset and the response on eye blinking dynamics. A silent period of 26 s was presented after the stimulus offset, followed by a response cue. The response cue was a “beep” with duration of 500 ms. The subjects were instructed to input the number of tones they counted using a numbered keypad immediately following the response cue. The response cue transiently evoked increased attention because the subjects had to find and press the correct key among 10 keys (0 to 9) while maintaining fixed eye contact on the screen. To mask the alerting effect of the response cue on eye blinking, identical tones were also presented at the time of the stimulus onset and offset. The intensity of the response cue was modulated to less than -7 dB relative to the stimulus tones because excessively loud, sudden sounds could evoke a reflex eyeblink.

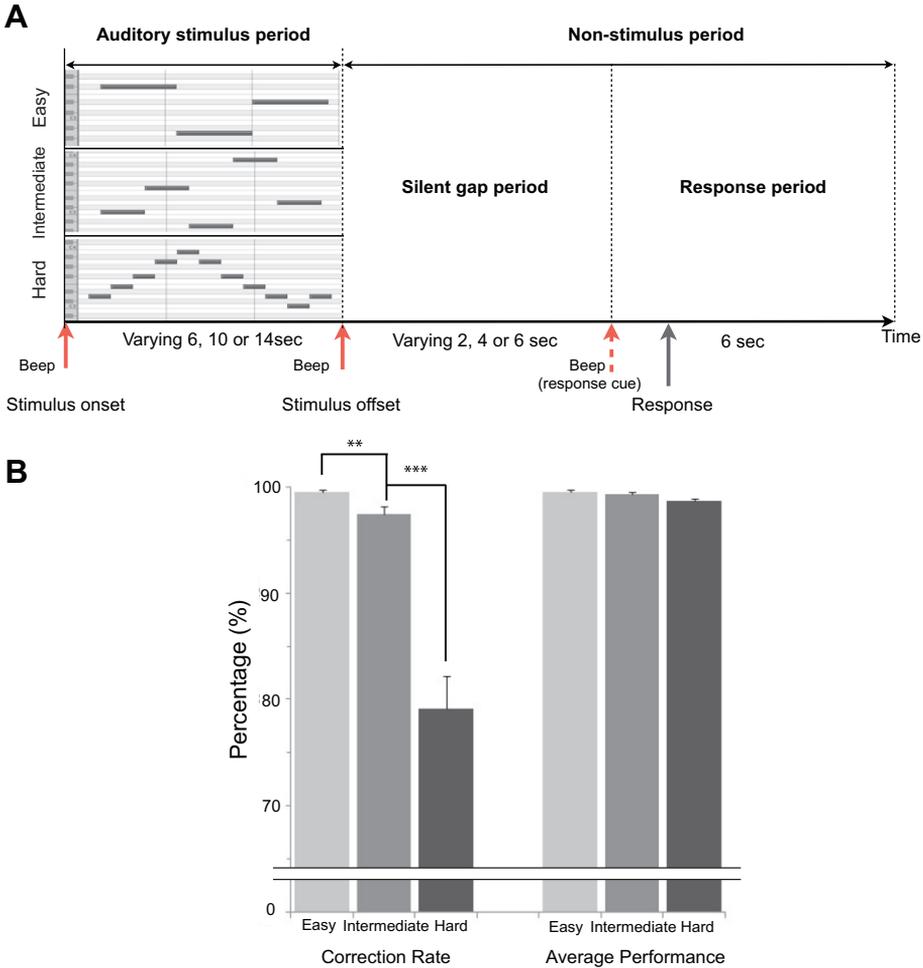
All subjects required two to three training sessions to properly respond immediately after the response cue using the number keypad while keeping their eyes fixed on the crosshair on the screen, as eyeblinks occurred when the subjects shifted their gaze. Nine sessions (10 trials/session) with different task difficulties (easy, intermediate, and difficult; three sessions for each) were presented to each subject in a random order. After the third session, we measured the resting eyeblink patterns for 2 min with the subjects’ eyes fixed on the screen.

## 2.3. Spectral and dispersion analysis

To assess whether self-organizing properties exist in eyeblink dynamics, we applied spectral density and fractal dimension analyses to each subject’s eyeblink time series. Each subject’s eyeblink intervals were collected with 10 Hz-sampling rate in each session (200 s duration). Because there were three different types of sessions (easy, intermediate, and difficult), we could classify each time series according to the stimulus difficulty.

The eyeblink interval data were preprocessed according to previously described methods (Delignières, Lemoine, & Torre, 2004; Eke et al., 2000). The mean of the interval series was subtracted from each value, a parabolic window was applied, and the interval data were linearly detrended (Eke et al., 2000). This step-by-step preprocessing approach has been shown to increase the relevance of the estimated slope in fractal analysis, particularly in a short time series (Delignières et al., 2006). Based on these preprocessed interval data, we measured the power-spectral density using a fast Fourier transform method. Next, we plotted the power-spectral density and frequency on a log-log scale. The slope of the line that relates power-spectral density to frequency in a log scale was estimated.

Each subject’s time-series of eyeblink intervals were subjected to a dispersion analysis that repeatedly resampled the data series using different sizes sampling bins to measure the fractal dimension of the time series. We applied five different sampling bin sizes (1000, 500, 100, 50, and 10 bins) and estimated the relative dispersion statistics, i.e., the ratio of the standard deviation and the mean ( $SD/M$ ).



**Fig. 1.** A schematic diagram for a trial in the auditory tone-counting task and its behavioral results. (A) During an auditory stimulus period (6, 10, or 14 s, randomly ordered), a series of tones was presented to the subjects at three different frequencies (0.5–5 tones/s), depending on the task difficulty. After the stimulus offset (punctuated by a cue sound), a silent gap period of 2, 4, or 6 s (randomly chosen duration) was presented that was followed by the response cue (beep, dashed arrow). The subjects were instructed to input the number of tones they counted using the number keypad immediately after the response cue. (B) Correction rate and related performances for the tone-counting task with three different task difficulties. Although the mean correction rates ( $n = 34$ ) differed significantly between the easy, intermediate, and difficult task conditions, there were no significant differences among different difficulty levels with regard to the subjects' overall performances.

Linear scaling between dispersion and sample size on log-log scales provided the linear slope of the dispersion analysis. The fractal dimension was determined by subtracting the slope of the linear regression from the value one.

2.4. Apparatus and data acquisition

Tasks were performed in a soundproof room where the EEG equipment was located. The subjects wore headphones (Bose, Inc., USA), and a fixation point was presented on the screen throughout the session. The room humidity was held constant at approximately 50% to ensure that drying of the cornea did not influence the rate of blinks.

We used the vertical and horizontal electrooculogram (vEOG) channel of a commercial EEG recording system (Compumedics Neuroscan, VA, USA) with a 32 Ag/AgCl electrode cap (Quick cap, Compumedics Neuroscan, VA, USA) to measure eyeblinks. The EEG cap was placed on the head, and the vEOG electrode was placed 10–15 mm above the upper eyelid and 20 mm below the lower margin of the eyelid. To prevent an awareness effect on spontaneous eye blinking, we told the subjects that the aim of the experiment was to obtain EEG recordings during the task. None of the subjects reported knowing that the timing and frequency of their eyeblinks were recorded when questioned after the experiment. STIM2 hardware (Neuroscan Inc. VA, USA) was used to synchronize the vEOG and the keyboard response; this system produced temporal cues whenever buttons were pressed, and these cues were recorded in the vEOG data. The analysis of eyeblink frequencies and patterns was performed using Neuroscan 4.3 (Neuroscan Inc., VA, USA).

Eyeblinks were determined in the following way. We used the 'voltage threshold transform' in Neuroscan EDIT (Neuroscan Inc., VA, USA) program to insert events at the thresholds for the peaks. Using the vEOG channel, thresholds were set to detect the onset of eyeblinks. Because the eyeblink signal had a voltage that was 50 times that of conventional noise, we could discriminate eyeblinks from noise (Kaneko & Sakamoto, 1999).

In the vEOG channel, the eye movement and eyeblinks were easily discernable; the eye movement altered the baseline in a stepwise function, and the eyeblink resulted in a peak response in the vEOG data. Because the subjects were required to fixate their eyes on the screen, few eye movements were observed (less than one percent of the number of eyeblinks). We also searched the onset of eyeblinks manually and cross-checked them.

### 3. Results

#### 3.1. Behavioral results

First, to confirm the effect of the difficulty levels on the task performance, we estimated the correction rate for each trial for all of the subjects. The correction rate was the ratio of correct answers in all trials. A correct answer was defined when subjects answered exactly the same number of tones as was presented. An analysis of variance revealed a main effect of stimulus difficulty (easy, intermediate, and difficult) on the correction rate (correction<sub>easy</sub> = 99.5%, correction<sub>intermediate</sub> = 97.4%, correction<sub>difficult</sub> = 79.1%; alpha level = 0.05,  $F = 36.8$ ,  $p < .001$ , respectively). These data indicate the distinct presence of three different levels of difficulty for the task (Fig. 1B).

We then measured the number of answered notes divided by the number of presented notes, which could indicate the subject's overall performance during the test (e.g., for a given trial, if 20 tones were presented, but a subject answered 18, we rated that trial as having 90% (18/20) correct answers). We found no significant difference among the three different difficulty levels in subject's overall performance (easy = 99.4%, intermediate = 99.2%, difficult = 98.6%; one-way ANOVA,  $F = 2.98$ ,  $p = .06$ , respectively) (Fig. 1B), although the frequency of tone presentation for the difficult trials was ten-fold higher than that for the easy trials. These results show that the subjects exhibited stable performance across all task difficulty levels.

#### 3.2. Eyeblink rates during three different time periods

A  $3 \times 3$  two-way repeated measures ANOVA with stimulus difficulty (easy, intermediate, and difficult) and time period (auditory stimulus, silent gap, and response) were tested for differences in the eye blinking rate. We found that the EBRs were significantly different among the stimulus difficulties ( $F = 17.19$ ,  $p < .001$ ). These main effects were supplemented by an interaction between the stimulus difficulty and time period (ANOVA interaction effect of difficulty  $\times$  time period,  $F = 3.77$ ,  $p < .05$ ). The results from the post hoc analysis with a Bonferroni correction demonstrated significant EBR differences between easy and intermediate ( $p < .001$ ), and between easy and difficult stimuli ( $p < .001$ ). However, there was no main effect of correctness on the eyeblink rate (difficult condition; one-way ANOVA,  $F = 0.22$ ,  $p = .64$ ).

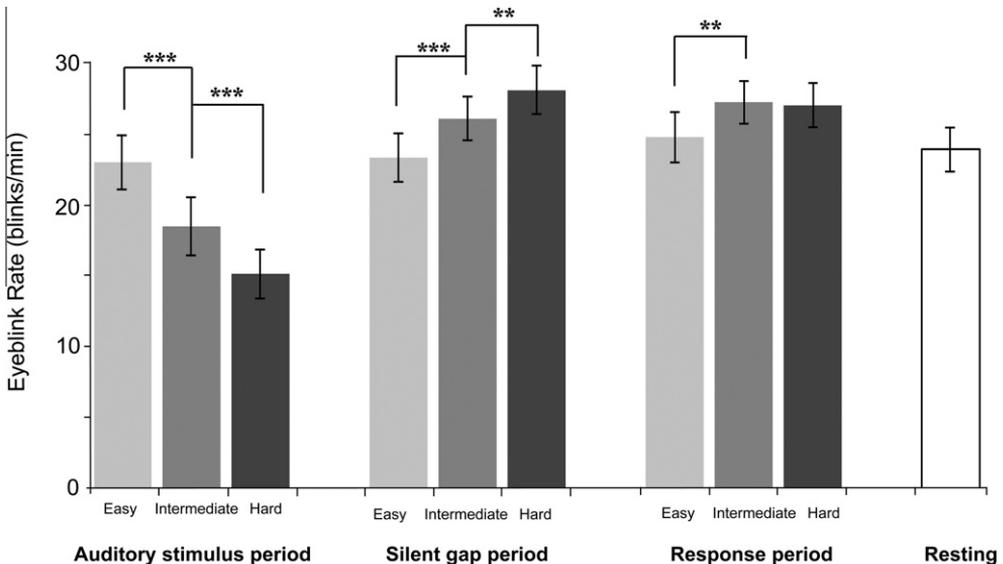
The analysis of eye blinking rates (EBRs, blinks/min) during the three different periods of the task revealed that the mean EBR significantly decreased during the stimulus period compared with the non-stimulus periods (i.e., silent gap and response periods) ( $EBR_{\text{stimulus}} = 18.9 \pm 10.9$  blinks/min,  $EBR_{\text{non-stimulus}} = 26.0 \pm 8.9$  blinks/min,  $M \pm SD$ ;  $n = 34$ , paired  $t$ -test,  $t(33) = 7.16$ , two-tailed,  $p < .001$ ) or the resting state ( $EBR_{\text{stimulus}} = 18.9 \pm 10.9$  blinks/min,  $EBR_{\text{resting}} = 23.9 \pm 9.2$  blinks/min;  $n = 34$ ,  $t(33) = 2.07$ ,  $p < .05$ ) (Fig. 2). These findings demonstrate that the increased attention during cognitive processes performed during auditory stimuli presentation suppressed the frequency of eye blinking, which was similar to the effect observed with visual presentations of stimuli.

Furthermore, we found that the EBR during the stimulus period decreased as the task difficulty increased (Fig. 2). The EBR decreased to a greater extent in the intermediate than in the easy tasks ( $EBR_{\text{easy}} = 22.9 \pm 11.2$  blinks/min,  $EBR_{\text{intermediate}} = 18.5 \pm 12.0$  blinks/min; paired  $t$ -test,  $T(33) = 6.89$ , two-tailed,  $p < .001$ ) and more in the difficult tasks than in the intermediate tasks ( $EBR_{\text{intermediate}} = 18.5 \pm 12.0$  blinks/min,  $EBR_{\text{difficult}} = 15.1 \pm 10.2$  blinks/min;  $T(33) = 4.68$ ,  $p < .001$ ). These findings indicate that the attention finely modulated the frequency of eyeblinks.

In contrast, EBRs increased during the silent gap period as the task difficulty increased ( $EBR_{\text{easy}} = 23.3 \pm 10.1$  blinks/min,  $EBR_{\text{intermediate}} = 26.1 \pm 8.8$  blinks/min;  $T(33) = 4.26$ ,  $p < .001$ ;  $EBR_{\text{intermediate}} = 26.1 \pm 8.8$  blinks/min,  $EBR_{\text{difficult}} = 28.1 \pm 10.1$  blinks/min;  $T(33) = 2.90$ ,  $p < .01$ ). This close association between the EBR and the task difficulty was also found during the response period, although it was weaker ( $EBR_{\text{easy}} = 24.8 \pm 10.6$  blinks/min,  $EBR_{\text{intermediate}} = 27.2 \pm 8.9$  blinks/min;  $t(33) = 2.56$ ,  $p < .05$ ;  $EBR_{\text{intermediate}} = 27.2 \pm 8.9$  blinks/min,  $EBR_{\text{difficult}} = 27.0 \pm 8.9$  blink/min;  $t(33) = 0.39$ ,  $p = .69$ ) (Fig. 2). We suggest that this correlation between increased EBR during the silent gap and response periods and the task difficulty likely arises from the rebound of the suppressed eye blinking during the stimulus period.

### 3.3. Temporal dynamics of eye blinking within a task

To investigate the role of attention for the temporal dynamics of eye blinking during a task, we estimated the temporal patterns of eyeblinks over the course of an entire trial in tasks with three different

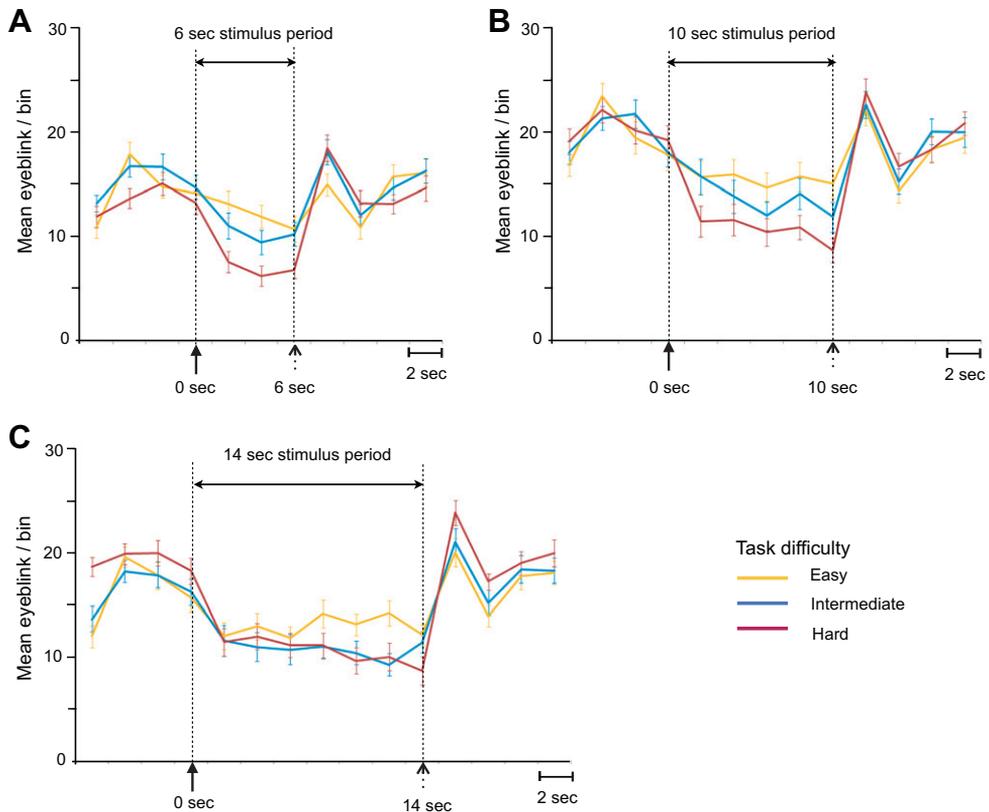


**Fig. 2.** Mean eyeblink rates (EBRs) ( $n = 34$ ) are shown for three different periods within a trial (i.e., the stimulus, silent gap, and response periods) in the three task difficulty conditions (easy, intermediate, and difficult). The EBR significantly decreased during the stimulus period as the level of task difficulty increased. In contrast, the EBRs increased during the silent gap period as the task difficulty increased. This relationship between the EBR and task difficulty was still observed during the response period, although it was weaker. Error bars denote the SEM. ( $*p < .05$ ,  $**p < .01$ ,  $***p < .001$ ).

stimulus durations (6, 10, and 14 s). The temporal profiles of the eyeblinks were similar in various stimulus durations (6, 10, and 14 s); the eyeblinks were suppressed during the stimulus period and were facilitated with a peak immediately following the stimulus offset (Fig. 3). In addition, the degree of eyeblink suppression and facilitation was associated with task difficulty.

We also assessed the eyeblink timing distributions toward the end of the three periods (the stimulus onset, stimulus offset, and response) for each trial, which were all signaled using identical cues (Fig. 4). We found that the spontaneous eyeblinks monotonically decreased around the stimulus onset time and did not exhibit a peak after the stimulus onset (Fig. 4A), even though the tone for the response cue was short and loud. In contrast to eyeblinks occurring around the time of the stimulus onset, spontaneous eyeblinks exhibited peaks of facilitation approximately 1 s after the stimulus offset and the response for each subject, as shown in the group histograms (Fig. 4B and C).

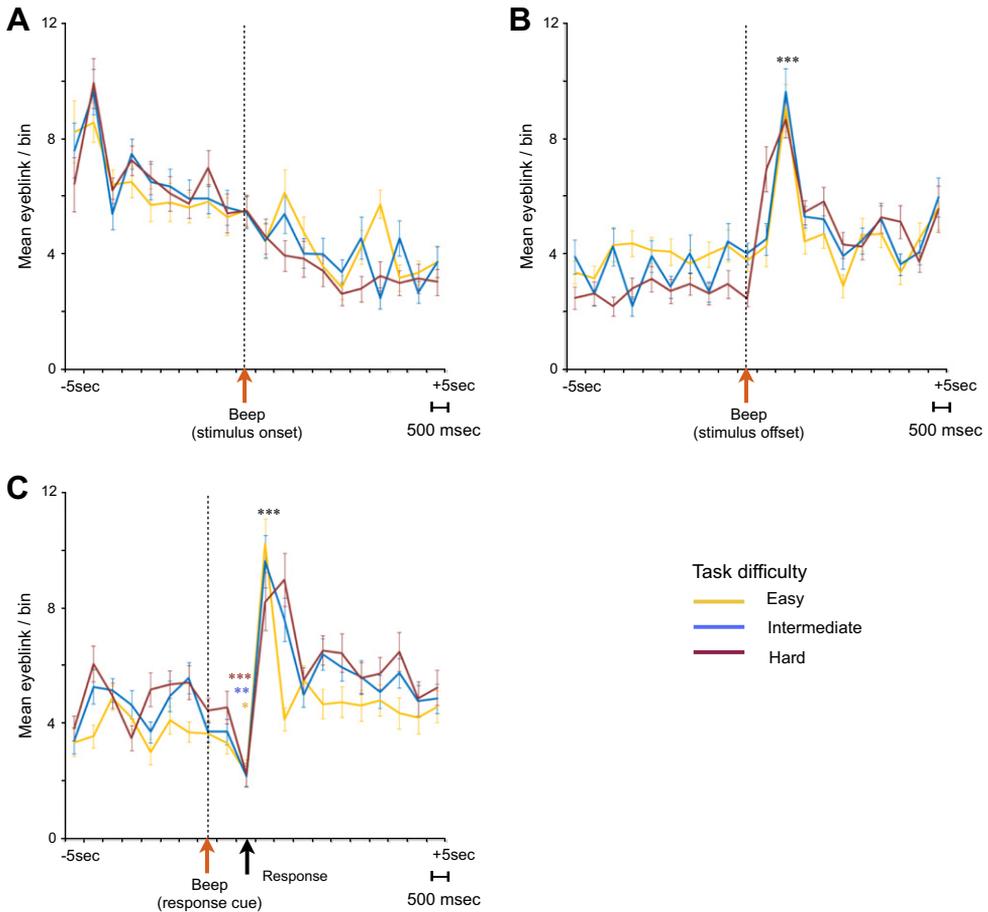
The peak eyeblink frequencies observed after the stimulus offset were not correlated with the difficulty of the task ( $\text{peak}_{\text{easy}} = 9.1 \pm 4.7$  blinks/bin,  $\text{peak}_{\text{intermediate}} = 9.6 \pm 4.6$  blinks/bin,  $\text{peak}_{\text{difficult}} = 8.6 \pm 3.5$  blinks/bin,  $M \pm SD$ ; one-way ANOVA,  $F = 0.43$ ,  $p = .65$ ), but the timing of the peaks became synchronized, with a bin size of 500 ms (Fig. 4B and C). The termination of the tones was marked by a tone near the stimulus offset, and the eyeblinks were facilitated with a peak at 1 s after the stimulus offset compared with the immediately preceding 1 s period. A  $2 \times 3$  two-way repeated measures ANOVA with EBR (1 s after the stimulus offset, 1 s before the stimulus offset)



**Fig. 3.** (A–C), Temporal patterns of eyeblinks over the course of an entire trial in the tasks with different stimulus durations ((A) 6 s, (B) 10 s, (C) 14 s). The temporal profiles of eyeblinks were markedly conserved for different stimulus durations. Colored lines are based on histograms with 2 s bins for tasks with three different levels of difficulty and for all trials for each subject ( $n = 34$ ). Eyeblinks were suppressed during the stimulus period and were facilitated at stimulus offset, with a peak immediately at the stimulus offset. The degree of suppression and facilitation for eyeblinks was associated with the level of task difficulty. Black arrows on the x-axis indicate the stimulus onset time, and the dashed arrows indicate the stimulus offset time.

and the stimulus difficulty (easy, intermediate, and difficult) as the variables revealed significant eyeblink facilitation after the stimulus offset ( $F = 211.38, p < .001$ ), but there were no interactions between the difficulty factor and the eyeblink timing ( $F = 0.15, p = .86$ ). Thus, the absence of peaks in the eyeblink distributions around the stimulus onset and the presence of peaks around the stimulus offset and response cue suggest that peaks in the silent gap and response periods were not a result of the alerting effect of the response cues but could be derived from the rebound of the suppression of eye blinking by attention during the stimulus period.

Importantly, we observed that eyeblinks were transiently suppressed between the response cue and the subjects' keypad response and that they were greatly facilitated following the response for all subjects (Fig. 4C). This transient suppression was significant for the group of subjects ( $2 \times 3$  two-way repeated measures ANOVA with eyeblink timing (transient suppression period and immediately preceding 500 ms period) and the stimulus difficulty (easy, intermediate, and difficult) as the

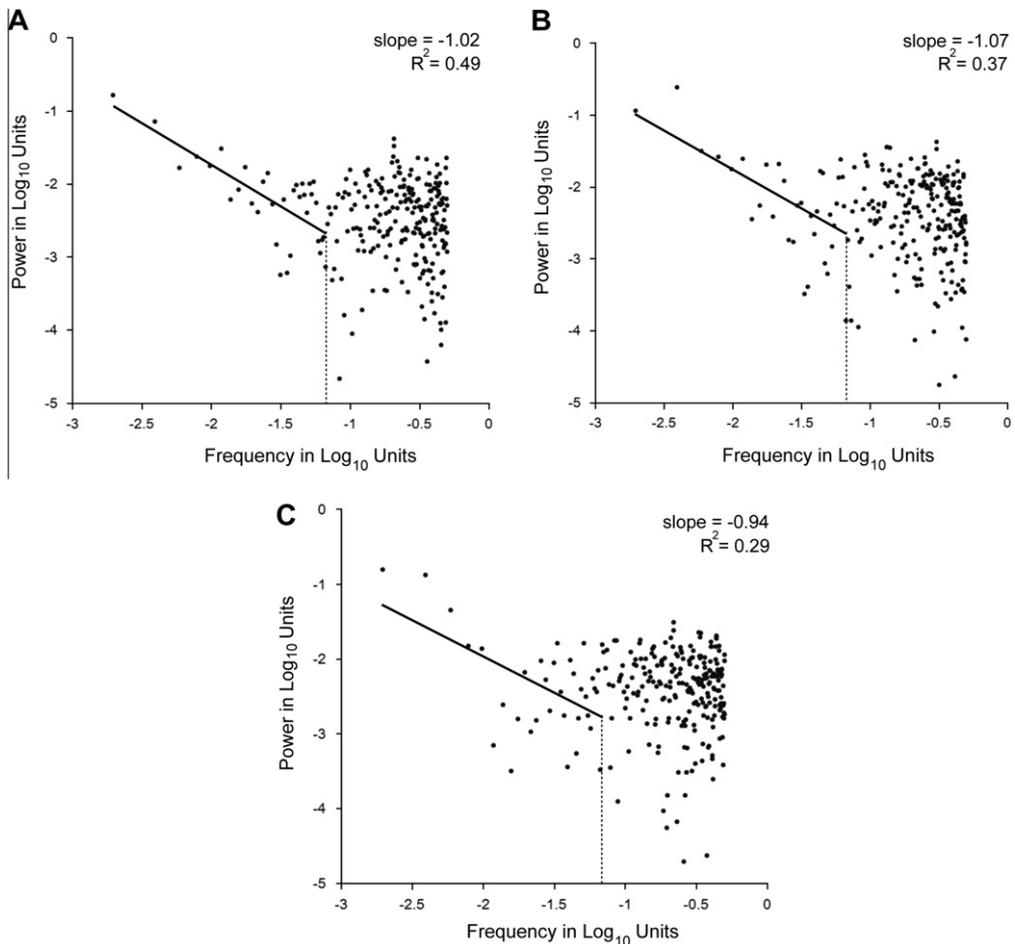


**Fig. 4.** (A–C), Eyeblink timing distributions around the transitions of the three periods (i.e., the stimulus onset, stimulus offset, and response) for all trials for each subject with a bin size of 500 ms ( $n = 34$ ). Beeps indicate the stimulus onset, stimulus offset, and response cue. (A), Eyeblinks monotonically decreased around the stimulus onset without any peaks. (B), The eyeblink distribution near the stimulus offset for tasks with three different levels of difficulty. After the termination of the series of tones was marked by a beep (the stimulus offset), the eyeblinks increased with a peak at 1 s. (C), The eyeblink distribution near the response. A beep was presented as a response cue, and the subjects pressed the keypad as rapidly as possible. Eyeblinks were suppressed for approximately 500 ms after the response cue and were facilitated immediately after the response. The interval between the response cue and the response was the reaction time, which was correlated with the duration of eyeblink suppression. Error bars denote the SEM. (\* $p < .05$ , \*\* $p < .01$ , \*\*\* $p < .001$ ).

main variables; main effect of eyeblink timing,  $F = 20.86$ ,  $p < .001$ ; main effect of stimulus difficulty,  $F = 1.00$ ,  $p = .37$ ; and interaction between the eyeblink timing and the stimulus difficulty,  $F = 1.12$ ,  $p = .33$ ). Similar to the peaks after the stimulus offset, we observed significant eyeblink facilitations following the response ( $2 \times 3$  ANOVA with eyeblink timing (500 ms before and after the response) and the stimulus difficulty as the variables; main effect of eyeblink timing,  $F = 144.38$ ,  $p < .001$ ; main effect of stimulus difficulty,  $F = 0.99$ ,  $p < .37$ ; and interaction,  $F = 0.92$ ,  $p = .40$ ). This eyeblink suppression was observed within the 500 ms before the response (Fig. 4D). In contrast, we did not find this transient suppression around the stimulus offset, which did not induce attention (Fig. 4B). We therefore suggest that attention dynamically modulates the temporal patterns of eye blinking at the sub-second time scale (the response period) and at the tens of seconds time scale (the stimulus period).

### 3.4. Spectral density and fractal dimensions of eyeblink time series

The spectral analysis of the subject is presented in Fig. 5. We delimited the low- and high-frequency regions of the individual spectrum analysis according to the methods presented in a study of tapping



**Fig. 5.** The power spectrum analysis results of the eye blinking interval data from one subject. The spectral results are presented with the frequency (x-axis) and power (y-axis) in log-log scales. The dashed line represents the points of inflexion, which delimit the low- and high-frequency regions (0.0631 Hz in this subject). The regression slope was measured from the low-frequency region of the power spectra. (A) = easy condition, (B) = intermediate condition and (C) = difficult condition.

and oscillatory motion (Delignières et al., 2004). Similar to the results obtained by Delignières' study, the boundary frequency of all of the spectra was within the range of 0.0625 to 0.1122 Hz.

In the low-frequency region, there was a negative slope between frequency and power (Fig. 5). The linear regression slope of this subject was  $-1.02$  under the easy condition,  $-1.07$  under the intermediate condition and  $-0.94$  under the difficult condition, which was similar to the characteristic slope of the  $1/f$  noise (approximately  $-1$ ). The mean slope value of all of the subjects was  $-0.58 \pm 0.42$  ( $M \pm SD$ ) under the easy condition,  $-0.64 \pm 0.48$  under the intermediate condition, and  $-0.65 \pm 0.43$  under the difficult condition. No main effect was observed for stimulus difficulty on the slope of the spectral density (one-way ANOVA,  $F = 0.21$ ,  $p = .80$ ). Because the proximity of the power spectra to  $-1$  implies the presence of  $1/f$  noise in the series (Delignières et al., 2004; Gilden et al., 1995), this finding suggests that the distribution of eyeblink dynamics might display  $1/f$  noise in the low-frequency region.

Using spectral analysis, we also estimated the fractal dimensions of each subject's eyeblink time series: a scaling relationship between the relative dispersion statistic (standard deviation/mean) and different sample sizes on log scale. A least square linear regression provided negative slope values for all of the subjects. The mean slope values were  $-0.35 \pm 0.11$  ( $M \pm SD$ ) under the easy conditions,  $-0.31 \pm 0.18$  under the intermediate conditions and  $-0.26 \pm 0.17$  under the difficult conditions. There was no significant effect of stimulus difficulty on the slope in the dispersion analysis (one-way ANOVA,  $F = 2.49$ ,  $p = 0.09$ ).

The fractal dimension, which subtracts the negative slope value from one, was  $1.35 \pm 0.11$  ( $M \pm SD$ ),  $1.31 \pm 0.18$ , and  $1.26 \pm 0.17$  in the easy, intermediate, and difficult conditions, respectively. Because the fractal dimensions of the  $1/f$  noise ranged from 1.2 to 1.5 (Van Orden et al., 2003), the eyeblink time series likely embedded decorrelated  $1/f$  noise in their occurrence.

## 4. Discussion

### 4.1. Alteration of eye blinking dynamics at the second to sub-second time scales

For the auditory tone-counting task used in this study, each trial consisted of at least three stages of information processing: (i) from the onset of the stimulus to the decision to make a response (the stimulus period), which is a stage that requires a considerable allocation of sustained attention; (ii) from the time when the decision to respond is made until the response cue (the silent gap period); and (iii) from the detection of the response cue to the completion of the response (the response period). We observed that eyeblinks were significantly reduced during the stimulus-processing period of high attention and were transiently suppressed during the response period. In contrast to the suppression of eyeblinks during the stimulus and response periods, the spontaneous eyeblinks increased as soon as the attention levels decreased and peaked approximately 1 s following the stimulus offset and response. This finding is consistent with previous studies that showed similar eyeblink bursts after visual and auditory Stroop (Oh et al., 2012; Siegle et al., 2008), discrimination (Fukuda, 1994), and typical semantic priming (Ichikawa & Ohira, 2004) tasks.

Our results demonstrated that spontaneous eyeblinks were significantly reduced during the stimulus-processing period of high attention and were facilitated immediately after the end of the stimulus. This suppressive and facilitative alteration of eye blinking dynamics was subject to the duration of the stimulus presentation, which lasted 6 to 14 s (Fig. 3).

Furthermore, a similar relationship between attention and eye blinking dynamics was also observed in the response period, which lasted less than one second. The eyeblinks were transiently suppressed immediately after the response cue and were facilitated immediately after the keypad response; however, there was no transient suppression of other auditory cues (stimulus onset and stimulus offset). In our study, only the response cue was related to the behavioral task; the subjects had to respond as quickly as possible after this cue. Thus, the task-relevant cue was the response cue, and the other cues were irrelevant. Because attention was contingent upon the task demands (Folk et al., 1992) and selective attention to behaviorally relevant stimuli enhanced neuronal responses (Fries, 2001), transient suppression of eye blinking during the response period might be related to increased attention to the task-relevant response cue.

A similar transient suppression of eye blinking was also found to occur in the startle eyeblink reflex. Pre-pulse inhibition of the startle eyeblink reflex refers to inhibition of the reflex eyeblink when a startling stimulus (e.g., a sudden, loud noise) is preceded by a non-startling stimulus (i.e., the lead stimulus) (Filion, Dawson, & Schell, 1998). This phenomenon is thought to occur via the direction of attention toward a lead stimulus, which inhibits the eyeblink reflex (Böhmelt, Schell, & Dawson, 1999; DelPezzo & Hoffman, 1980). Although the reflex and spontaneous eyeblinks may have different physiological generation mechanisms and functional roles (Kaneko & Sakamoto, 1999), this transient suppression of spontaneous eyeblinks during a short attention-demanding period suggests that modulation of the temporal pattern of spontaneous eye blinking on a short time scale is similar to that of a startle reflex.

Our finding of a fast alteration of eye blinking dynamics both at the second time scale (during the stimulus presentation period) and at the sub-second time scale (during the response period) suggests that the occurrence of eye blinking has similar temporal structures at multiple time scales during cognitive processing. These results imply that eye blinking time series might have a  $1/f$  scaling property, which is ubiquitous in various human forms of cognition, movements, and other scientific fields (Gilden et al., 1995; Van Orden et al., 2003; Van Orden, Holden, & Turvey, 2005).

#### 4.2. $1/f$ scaling noise in the dynamics of eye blinking

The  $1/f$  noise is a signal with a power spectral density that is inversely proportional to the frequency; it is observed in self-organizing behaviors (Van Orden et al., 2003) and is commonly found in the behaviors of biosystems. The  $1/f$  noise is ubiquitous in various human cognitive systems, such as in lexical decision making, serial and parallel visual searches (Gilden, 2001), simple reaction time series (Van Orden et al., 2003) (Van Orden et al., 2005) and error sequences in replicating given targets (Gilden et al., 1995). The  $1/f$  noise was also discovered in voluntary and involuntary human movements, such as heartbeat intervals (Peng et al., 1993), gait sequences during walking (Hausdorff et al., 1996), gait sequences during metronomic walking (Delignières & Torre, 2009) and in tapping tasks (Delignières et al., 2004).

Despite a number of studies reporting  $1/f$  noise in human performances, whether there is a  $1/f$  scaling property in eye blinking has not yet been investigated. In this study, we measured the spectral density and fractal dimension of an eye blinking time series and found that the pattern of eye blinking demonstrates  $1/f$  noise. The fractal dimension of all of the subjects was  $1.34 \pm 0.09$  ( $M \pm SD$ ) and ranged from 1.05 to 1.50 across subjects. A fractal dimension of 1.5 with a jagged and irregular line is known to represent white noise, and fractal dimensions ranging from 1.2 to 1.5 represent the region of  $1/f$  noise. Moreover, a fractal dimension of less than 1.2 could represent Brownian noise (Holden, 2005; Van Orden et al., 2003). In our data, 1 of 34 subjects exhibited a fractal dimension that was lower than 1.2, which indicates Brownian noise. Two of the 34 subjects had a fractal dimension of 1.50, which is a borderline value between white and  $1/f$  noise. The rest of our subjects (31 subjects) had a fractal dimension within the range of the  $1/f$  noise. Thus, our results show that the dynamics of eye blinking under a specific cognitive task might have a self-organizing structure.

It has been suggested that  $1/f$  noise originated from self-similar conditions that involve stationary random stochastic processes (Szendro, Vincze, & Szasz, 2001) and that self-organized criticality is related to the emergence of the  $1/f$  scaling property (Van Orden et al., 2005). Thus, our findings of a similar temporal pattern at local time scales (seconds and sub-second) could be related to the observed  $1/f$  noise at the broad time scale. Because a similar  $1/f$  noise in a spontaneous stride interval is thought to be related to the neural centers that control walking (Hausdorff et al., 1996), the fractal dynamics of eye blinking could have originated from the motor nucleus of the facial nerve located in the pons or orbitofrontal cortex, which are activated during spontaneous eye blinking (Dimitrova et al., 2002). Furthermore, because our eye blinking data were obtained under conditions of sustained or transient attention, the processing of specific cognitive tasks could be responsible for the self-similar fluctuation of eye blinking dynamics. The results presented in this study suggest that the occurrence of spontaneous eye blinking has a scale-free, self-similar structure that also prevails in other human movements.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.humov.2012.06.003>.

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