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Temporal processing underlying transient twinkle perception in luminance and chromatic stimuli

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Abstract: Humans can detect transitions of frequencies between two sequentially presented flickering stimuli, even when the two flickering stimuli appear steady, a phenomenon known as transient twinkle perception (TTP). A previous study of TTP has suggested that a temporal integration model with a monophasic Gaussian filter can account for this effect. However, the low-level temporal integration of the human visual system for luminance stimuli has been characterized by a biphasic filter. Here, we measured TTP magnitude under various conditions and evaluated Gaussian and bi-phasic filter models. In Experiment 1, we examined the effect of frequency differences between the first and second epochs on TTP magnitude. Experiments 2 and 3 introduced intermediate frequency frames to gradually transition between flickering frequencies. Experiment 4 assessed TTP magnitude using equiluminant chromatic stimuli. Results showed that, for luminance-based TTP, the bi-phasic filter model better accounted for TTP magnitudes, whereas the Gaussian filter model aligned more closely with TTP magnitude observed in the equiluminant chromatic condition. These findings suggest that both luminance and chromatic TTP are natural outcomes of the temporal integration in low-level visual processing and that an ad hoc model for TTP is unnecessary.

1. Introduction

The human visual system has a limited temporal resolution, and the critical flicker fusion (CFF) threshold is a representative measure characterizing this limit. When the temporal frequency of a flickering stimulus exceeds the CFF, the flickering stimulus is perceived as steady without noticeable flicker. Previous studies have reported that the CFF ranges from 50 to 100 Hz, depending on various factors such as mean luminance [1–3], stimulus size [2,4], and viewing distance [5]. The CFF is especially important for its practical significance, providing a standard reference for determining temporal resolution in the display industry.

Interestingly, however, there are several spatiotemporal visual patterns in which the human visual system can discern a flickering stimulus with a frequency higher than the CFF [6,7]. Transient twinkle perception (TTP) is one such phenomenon [8,9]. TTP refers to the perception of a flash that occurs when frequencies of two sequentially presented flickering stimuli change. For example, Fig. 1(A) illustrates luminance changes in a typical TTP stimulus, where flickering frequencies change between the first and second epochs. Even when the frequencies of the two epochs surpass the CFF and both appear as steady, a twinkle can be perceived at the transition between the two frequencies (Fig. 1(B)).

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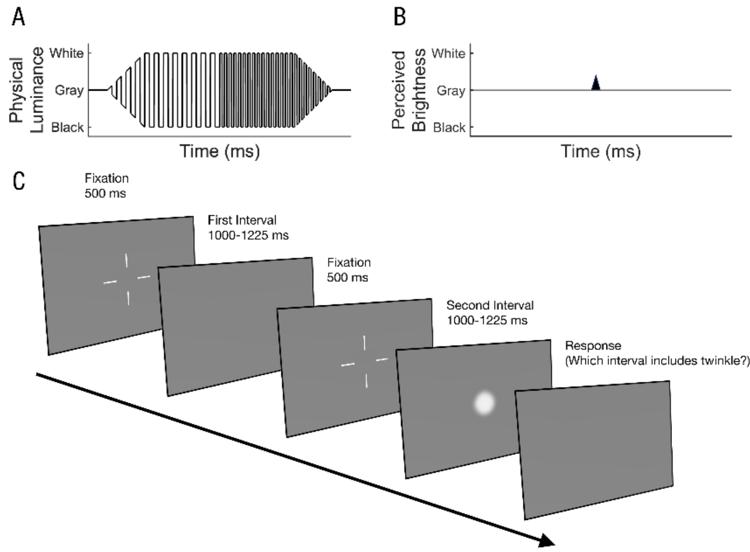

Fig. 1. A TTP stimulus. (A) Physical luminance of flickering stimulus over time referred to the previous study [8]. The first and second epochs have different temporal frequencies higher than the Critical Flicker Fusion (CFF) threshold. The luminance profile at the beginning and end of the stimulus was temporally enveloped to prevent transient twinkling at the start and end [9]. (B) Perceived luminance of the TTP stimulus over time. The flicker is not detected during the first and second epochs; however, the twinkle is detected during the transition between two epochs. (C) The assessment of contrast thresholds for TTP stimuli using a two-interval forced-choice (2-IFC) task. An illustration of a single trial. Participants were asked to report which interval contained the flickering stimuli after two intervals were consecutively presented.

It has been proposed that TTP reflects the temporal filter properties of the low-level visual system. Specifically, Nakajima and Sakaguchi [8] suggested that a moving-average model with a Gaussian temporal filter can effectively capture the TTP magnitudes observed in their study. While the low-level visual system is known to function as a spatiotemporal filter, as their model supposes, the kernel shape suggested by the model, a Gaussian, is not consistent with existing literature. Existing studies convergingly show that the kernel of the temporal filter in the low-level visual system is biphasic, which has a short excitatory phase followed by a longer inhibitory phase, rather than monophasic when the mean luminance of the stimulus is relatively high [10–12]. The biphasic kernel is also consistent with the band-pass properties of the temporal contrast sensitivity function [3,13,14].

There could be two possibilities for this apparent discrepancy in literature. First, it is plausible that TTP is a product of higher-level visual processing beyond the low-level filter and, consequently, does not reflect the properties of the low-level temporal filter. Second, TTP indeed is a product of the low-level temporal filtering; however, the stimuli used in the existing TTP study [8] are not sensitive enough to discern a monophasic and a biphasic kernel shape.

In this study, we adopted stimuli with diverse temporal frequency patterns to critically test whether a Gaussian filter model or a biphasic filter model can account for the TTP magnitude better. In Experiment 1, we examined the effect of frequency difference between the first and second epochs on TTP magnitudes to replicate the existing study. In Experiment 2 and 3, we inserted ‘in-between’ frequency frames to gradually change the flickering frequency between epochs. In Experiment 4, we measured the TTP magnitude with an equiluminant chromatic stimulus that alternated between red and green. The kernel of temporal filter for chromatic stimuli is known to be monophasic unlike that for luminance stimuli [15]. If TTP does reflect the properties of the low-level temporal filter, and our stimuli set is sensitive enough to discern the kernel shape, it is expected that a biphasic filter model would fit the TTP of luminance stimuli (Exp 1, 2, 3) better, while a Gaussian filter model would fit the results of chromatic stimuli (Exp 4) better. The results of our experiments are largely consistent with this prediction, suggesting that TTP can be explained by known temporal properties of the low-level visual system. Furthermore, we observed that magnitudes of TTP substantially fluctuate in response to subtle temporal modulations of stimuli in Experiment 3 and 4, and our models capture those patterns closely. This result highlights the practical usefulness of the model in industrial applications.

2. Method

2.1. Participants

Experiment 1 and 2 involved 7 participants (mean age 23.71 ± 2.69, 5 males). Experiment 3 included 11 participants (mean age 23.71 ± 2.72, 7 males), with one of the authors participating. Experiment 4 included 11 participants (mean age 21.34 ± 3.32, 3 males), with two of the authors participating. All participants reported having normal or corrected-to-normal vision and completed the experiment with their habitual optical correction (e.g., glasses or contact lenses). Although their visual acuity was not formally assessed, minor refractive differences are unlikely to have influenced performance, as the task involved detection of the temporal pattern of a flickering stimulus and did not require high visual acuity. All participants received instructions on the experiment before it began. The experimental procedures received approval from the Ulsan National Institute of Science and Technology Institutional Review Board (IRB) with the approval number: UNISTIRB 22-08-A, dated 2022.03.01.

2.2. Apparatus

All stimuli were presented on a Digital Light Processing (DLP) projector (PROPixx, 1920×1080 pixels, maximum luminance of 182 cd/m^2) and created by MATLAB and the Psychophysics Toolbox [16]. The PROPixx presents flickering stimuli at a higher temporal frequency, up to 1440 Hz, by splitting a 120 Hz screen into 4 quadrants and converting RGB channels to grayscale. In chromatic stimulus, its refresh rate can be increased as 480 Hz without converting RGB channels. The temporal frequencies of the flickering stimulus were selected from the possible temporal frequencies, considering the method by which the PROPixx achieves higher temporal frequencies. Throughout the experiment, participants sat in a dark room (0.15 cd/m^2). Due to the dark room setup, the viewing distance was set to 160 cm. However, this level of accommodative demand is not expected to affect performance in detecting flickering stimuli presented at the center of the screen.

2.3. Stimulus

Circular patches with a fixed diameter of 1 degree of visual angle were presented at the center of the screen. All stimuli were spatially enveloped by a raised cosine filter from the center of the screen to remove the perception of a sharp edge. To prevent the visible twinkle at the onset/offset of the stimulus, the contrast of flickering stimuli was temporally ramped by linearly increasing from 0% to its target contrast over 176 ms at the onset, and then decreases back to 0% over another 176 ms at the offset, as previous research suggested [9]. Each stimulus consisted of two distinct epochs. In each epoch, a flickering stimulus was presented, alternating between white and black with its own temporal frequency (Fig. 1(A)). For example, in one stimulus, the flickering might occur at a temporal frequency of 72 Hz during the first epoch and then switch to a higher frequency of 144 Hz during the second epoch.

In luminance stimuli as Experiment 1~3, when its temporal frequency was above the CFF, its flickering perceived discernible with gray screen, [0.299 0.318] as CIE xyz with the mean luminance, 87.45 cd/m^2. Also, the luminance of the background is fixed as 87.45 cd/m^2 with gray color, [0.299 0.318]. In Experiment 4, chromatic stimuli were used, where chromatic contrast was varied between red and green, [0.409 0.309] and [0.197 0.314] as CIE xyz with the same mean luminance, 87.45 cd/m^2. Also, the gray screen was fixed with [0.303 0.312] as the mean value between two chromatic contrasts, with same mean luminance, 87.45 cd/m^2. The contrast was computed by Michelson Contrast in this study as Eq. (1)**.**

$$\boldsymbol{C} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

where I_{max} is the maximum intensity of the dimension. In luminance stimuli, I_{max} determined the white, in chromatic stimuli, it determined the red.

Experiment 1: The first epoch's frequency was either 72 Hz or 120 Hz. The last epoch's frequency was set to 60, 72, 80, 90, 120, or 144 Hz. We excluded the conditions where the temporal frequencies of the two epochs are the same, assuming their contrast threshold to be 1. This is because there was no transition in terms of temporal frequencies, and since the temporal frequencies were above the CFF, participants could not detect the flicker.

Experiment 2: The flickering stimulus in Experiment 2 was created by inserting 'in-between' temporal frequency epoch between the first and last epoch. The 'in-between' temporal frequency refers to the frequencies of the frames that lie between the first epoch of frequency before the frequency transition and the last epoch of frequency after the frequency transition. During the 'in-between' epoch, the temporal frequency gradually changed, as illustrated in Fig. 2(B). In this example, when the temporal frequency transited from 72 Hz to 144 Hz, 12 frames of 'in-between' frequencies (80, 90, and 120 Hz) were inserted (6.25, 5.56 and 4.17 ms, respectively).

Experiment 3: The length of the 'in-between' frequency epochs varied by manipulating the number of frames presented at each temporal frequency. For example, 0 frame/each frequency indicated no insertion of 'in-between' frequencies, replicating the stimuli used in Experiment 1. The number of frames for each frequency varies from 0 to 13 frames. When the number of frames is odd, the polarity of the consecutive frames was assigned in a non-overlapping manner. The temporal frequencies of the first and last epochs were fixed at 72 Hz and 144 Hz, respectively.

Experiment 4: Chromatic stimuli were generated using alternating equiluminant red and green patches. Temporal frequencies of chromatic stimuli were adjusted based on the capabilities of PROPixx (see Apparatus). The temporal frequency of the first epoch is 40 Hz, while the second epoch is set at 120 Hz. In this condition, in-between' frequencies of 48, 60, and 80 Hz were employed, with the number of frames varying from 0 to 8 frames for each 'in-between' frequency. The range of temporal frequencies were decided considering lower temporal sensitivity of human vision in chromaticity [13].

2.4. Procedure

Before the experiment began, participants underwent a 10-second adaptation period to a gray screen with a mean luminance of 87.45 cd/m^2. A two-interval forced-choice (2-IFC) task was employed to assess participants' ability to detect the Transient Twinkle Perception (TTP). The procedure for each trial is illustrated in Fig. 1(C). Each trial began with a 500 ms fixation interval. To avoid the effects of visual persistence at the center, the fixation point consisted of four rectangular lines (0.05×0.5 deg), arranged in a cross shape at 2 degrees eccentricity. Two consecutive stimulus intervals were followed, separated by a 500 ms blank interval. One interval contained the TTP stimulus, while the other presented a non-TTP stimulus. The non-TTP stimulus was either high-frequency gray flicker in luminance presentation (as used in Experiment 1-3, 1440 Hz) or high-frequency red-green flicker in chromatic presentation (as used in Experiment 4,

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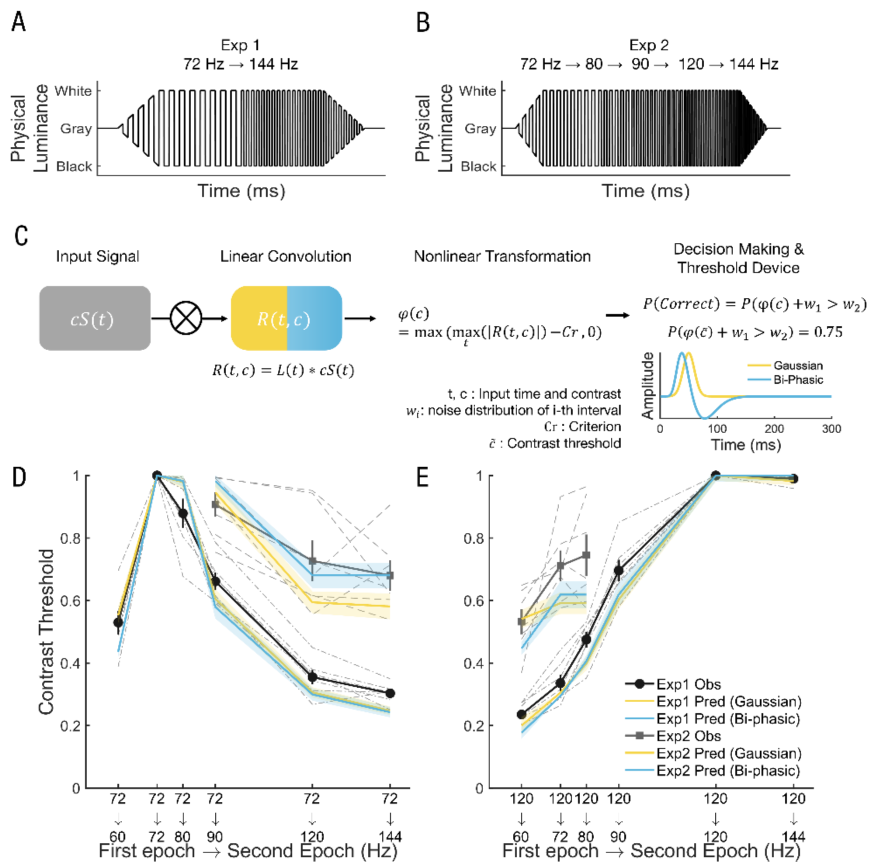

Fig. 2. Experiment 1 and 2, and Temporal integration model. The physical luminance profile of flickering stimuli used Experiment 1 and Experiment 2, respectively (A and B). The profiles were simplified for illustrative purposes. The x-axis denotes time in milliseconds (ms), and the y-axis represents physical luminance. (C) The diagram of temporal integration model with the Gaussian and bi-phasic temporal filter. Two filter models with the Gaussian (yellow) and bi-phasic (cyan) filters were simulated. The input signal, temporal modulation with a specific contrast, is linearly convoluted with the temporal filter and then nonlinearly transformed before the decision making and threshold device (see Model Description in Method). (D and E) Contrast thresholds for TTP stimuli from Experiment 1 (Black) and Experiment 2 (Gray). The x-axis represents the difference between the temporal frequencies of the first and last epochs, and the y-axis represents the contrast threshold for each condition. Figure 2(D) shows contrast thresholds when the temporal frequency of the first epoch is 72 Hz, and Fig. 2(E) when the first epoch is 120 Hz. Error bars indicate mean contrast thresholds with standard errors of means, while thin lines represent individuals' data, non-dotted line is from Experiment 1 and dotted line is from Experiment 2. The model predictions were plotted in different colors, yellow (Gaussian), and cyan (Bi-phasic). The standard error of the model prediction was shaded in each color. Note that the contrast thresholds are assumed to be 1 when there was no change in terms of temporal frequencies.

240 Hz), maintaining the same luminance as the mean luminance of TTP stimulus to ensure no perceived twinkle. The order of TTP and non-TTP stimulus presentation was randomized across trials.

Participants were asked to report the interval containing the twinkle stimulus after observing the two intervals. They had no time limit for responding and received audio feedback on the accuracy of their choice. The contrast threshold, representing the ability to detect TTP, was estimated using the QUEST method [17]. This adaptive procedure adjusted the contrast of subsequent trials based on the correctness of participants' response. Each experimental condition has 80 trials to estimate contrast sensitivity. For instance, in Experiment 1, which included 10 conditions varying temporal frequency from 72 Hz to 60, 80, 90, 120, and 144 Hz, and from 120 Hz to 60, 72, 80, 90, and 144 Hz, participants completed 10 adaptive QUEST chains with the intermixed presentation order. The experiment was divided into blocks, each containing 80 trials. Experiments 1 and 2 were conducted over two separate days, with a total duration of approximately 3 hours. Experiments 3 and 4 were completed in a single day, each lasting about 2 hours. Breaks were provided as needed to minimize fatigue.

2.5. Data analysis

The repeated-measures ANOVA was conducted on the contrast thresholds to investigate the effect of the manipulation of TTP stimulus. Across all experiments, participants were used as a random factor. In Experiment 1, the frequencies of the second epoch were used as fixed factors. In Experiment 2, the effect of the insertion of 'in-between' frequency epochs was used as fixed factors. In Experiment 1 and 2, the ANOVA was conducted separately with each frequency of first epoch, 72 Hz and 120 Hz, to see any difference between the increasing transition from 72 Hz and the decreasing transition from 120 Hz of frequency. In Experiment 3 and 4, the length of the 'in-between' frequency epochs, as the frame of each 'in-between' frequency epoch, and the effect of the frame oddity were used as fixed factors accordingly. For post-hoc analysis, the Tukey test was performed to determine which lengths of 'in-between' frequency epochs were significantly grouped with the contrast threshold in Experiments 3 and 4. All analyses were performed using R Statistical Software (ver. 4.4.0).

3. Temporal integration model

3.1. Model description

This model aims to predict contrast thresholds for the luminance and chromatic TTP stimuli within the framework of temporal integration model without considering spatial properties. Input signal is a flickering stimulus alternating its contrasts, mimicking the physical stimulus of the screen. In the luminance stimulus, a contrast level has a value of 1 for the white frame with maximum luminance of the projector and -1 for the black frame with minimum luminance of the projector. In the equiluminant chromatic stimulus, a contrast level has a value of 1 for the red and -1 for the green. After that, we multiplied 100 times of the contrast level to amplify the signal. The time step of the input stimulus is 1/1440 seconds, as the maximum refresh rate of the projector. The input signal multiplied by contrast, $cS(t)$, was linearly convoluted by the temporal filter, $L(t)$, as Eq. (2). The temporal integration model is categorized by the type of filter, the Gaussian filter and the bi-phasic filter.

$$R(t, c) = L(t) * cS(t) \tag{2}$$

(1) Gaussian filter Model: The Gaussian temporal filter used in previous study [8] is implemented as written in Eq. (3). It indicates the Gaussian distribution over time τ whose window is $6x$, peak is $3x$, and sigma is x. While the original model used the scale parameter and signal-to-noise ratio with fixed criterion to predict the detectability of TTP after linear convolution, this model employed the threshold device considering the nonlinear

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processing in early vision after the linear filtering [18–20], which will be explained later.

$$G(\tau, x) = \frac{1}{x\sqrt{2\pi}} \exp\left(-\frac{(\tau - 3x)^2}{2x}\right) \tag{3}$$

(2) Bi-phasic filter Model: This study incorporates the bi-phasic filter model, given its relevance in explaining temporal contrast sensitivity functions [11,12]. The bi-phasic filter is constructed as the difference between two gamma functions defined by Eq. (4), a common approach in neurological studies [21–23]. There is a parameter, rate parameter x, was multiplied the initial filter as Eq. (4)**.** The initial filters ([15.246, 0.0027, 1.981] for k_1, k_2, and k_3) were obtained by fitting temporal contrast sensitivity function (tCSF) to 9300 td at mean luminance [3]. The inverse Fourier transform of the tCSF is established as a standard method for obtaining bi-phasic temporal integration filters in many previous studies [11,12,24].

$$B(\tau, x) = gampdf(\tau, k_1, k_2x) - gampdf(\tau, k_1, k_2k_3x) \tag{4}$$

Where $gampdf(t, a, b) = \frac{1}{(a-1)!b^a} t^{a-1} e^{-\frac{t}{b}}$, and fixed parameters, $k_1 = 15.246$, $k_2 = 0.0027$, and $k_3 = 1.9814$, which estimated from TCSF's data [3].

The output from the linear convolution was subjected to non-linear transformation, as we focused solely on the detectability of the temporal signal. It indicates non-linear transformation from linear convolutional output to perceptual magnitude. This process includes two steps: First, converting the output to scalar by extracting the maximum response from the absolute value of the output to determine the detectability; second, applying a max function that establishes a low bound for perception by setting the value to zero if it falls below the criterion. The equation of non-linear transformation is shown in the Eq. (5) below:

$$\varphi(c) = \max\left(\max_t(|R(t, c)|) - Cr, 0\right) \tag{5}$$

The perceived magnitude, $\varphi(c)$, is the maximum of the absolute value of the convolution output minus a criterion, Cr. If $\varphi(c)$ is below zero, it is set to zero. The signal and non-signal intervals are contaminated by random noises w_1 and w_2, which follow a normal distribution with a mean of zero and a variance of σ^2.

Following the non-linear transformation, the decision making was conducted. In the experiment, participants decided whether the twinkle was perceived in the first or second interval. In this decision-making process, if the twinkle occurred in the first interval, the probability of the participant correctly identifying the interval followed the Eq. (6). In the Eq. (5), $\varphi(c) + w_1$ is signal stimulus which has the twinkle with the noise, and w_2 is the noise stimulus. The noise distribution of i-th interval, w_i, was assumed for Gaussian function whose mean is 0, and variance is σ^2. The noise distribution of every stimulus had an identical assumption. This decision-making process predicted that participants choose the interval with the larger response value. We also estimated the contrast threshold, which made the probability of correction equal to 0.75 in Eq. (6).

$$P(Correct) = P(\varphi(c) + w_1 > w_2) \tag{6}$$

Participants' responses were fitted to the temporal integration model individually using the maximum likelihood method in the Eq. (7). This process involved optimizing three parameters: a single parameter for each filter (Gaussian filter and Binocular filter: x) and two parameters representing the decision making (Cr and σ).

$$L = \prod_i^n \phi(\theta_i)^{y_i}[1 - \phi(\theta_i)]^{1-y_i} \tag{7}$$

where θ_i is the estimated response for i-th trial, and y_i is the i-th response (1 for the correct response, 0 for incorrect response).

3.2. Model comparison

We employed the Akaike Information Criterion (AIC) [25] to compare the performance of the two models. We computed the difference in AIC values (ΔAIC) between the two models, by subtracting the AIC of bi-phasic filter to AIC of Gaussian filter. The negative ΔAIC means that Gaussian filter model explains the results better than bi-phasic filter and vice versa. Lower AIC values indicate a higher explanatory power for the observed results.

$$AIC = -2 \ln L + 2k \tag{8}$$

where k is the number of parameters, and L is likelihood from Eq. (7)

This ΔAIC is equal to the log likelihood ratio because the number of parameters was same (three in both models), as defined in Eqs. (3) and (4). Therefore, we conducted a one-sampled t-test in the ΔAIC from 0 to determine its polarity and find a significant difference between the performance of two models.

4. Results

4.1. Experiment 1: effects of temporal frequency difference between the two epochs on TTP

Previous research has shown that the magnitude of TTP increases as the difference between the temporal frequencies of two epochs increases [8]. We replicated this finding by measuring TTP magnitudes while manipulating the temporal frequency of the second epoch given a fixed frequency of the first epoch. Results are shown in Fig. 2. Black circles with error bars in Fig. 2(D) represent contrast thresholds when the temporal frequency of the first epoch is 72 Hz, and those in Fig. 2(E) represent contrast thresholds when the temporal frequency of the first epoch is 120 Hz. For conditions without a change in flicker frequency (72 Hz → 72 Hz, 120 Hz → 120 Hz), the contrast threshold was marked as 1, indicating that flicker was not detectable at the maximum contrast. The results show a consistent pattern: contrast thresholds gradually decrease, meaning that TTP magnitudes increase as the difference between two epochs' temporal frequencies increases, regardless of whether the frequency of the first epoch is lower or higher than that of the second epoch.

Repeated-measures ANOVA revealed a significant main effect of the difference between the two epochs' temporal frequencies in both increasing and decreasing temporal frequencies (First epoch's frequency 72 Hz: $F_{4,24} = 124.50$, $\eta = 0.95, p = 1.11 \times 10^{-15}$; 120 Hz: $F_{4,24} = 389.50$, $\eta = 0.98, p = 2 \times 10^{-16}$). The results of Experiment 1 demonstrate that TTP magnitude significantly increases as the difference between the temporal frequencies of two epochs increases, replicating the findings of previous research [8].

A temporal integration model was used to explain the results of the experiments (Fig. 2(C); see Model Description for details). The temporal integration model considered two types of temporal filters, $L(t)$, as shown in Fig. 2(C) (see Model Description for details). The first type, a Gaussian filter model, was introduced in a previous study to explain the results of TTP detection tasks [8]. The second type, a biphasic filter model, has been proposed in studies related to the temporal integration process in human vision [10,11]. We fitted the two types of models with each participants' responses to investigate and compare the model performances. In model fitting, both models had three free parameters: the temporal width of the filter, the criterion Cr, and the variance of noise distribution σ^2. We compared the performance of two models using the difference in AIC (see Model Comparison for details).

Since Experiments 1 and 2 shared the participants, we fitted the results of Experiment 1 and 2 simultaneously. As results of model prediction, both the bi-phasic (cyan) and Gaussian filter (yellow) models predict the effects of temporal frequency changes on TTP and provide good fits to the results from Experiments 1 and 2 (Fig. 2(B) and (C), see Figure S1 for individuals' fit).

The ΔAIC shows there was no significant difference between two models (see Table S1; ΔAIC: t_6 = .344, p = .742). The results from Experiment 1 and 2 were well explained by both models, bi-phasic and Gaussian filter models.

4.2. Experiment 2: effects of ‘in-between’ frequency epoch on TTP

The results of Experiment 1 showed that the TTP magnitudes increased as the frequency changes between the two epochs increased. This suggests that TTP magnitudes can be modulated if the temporal frequency gradually changes from the first epoch to the second epoch by inserting ‘in-between’ frequencies (Fig. 2(B)). In Experiment 2, we tested this hypothesis. The flicker frequencies of the first epoch were either 72 or 120 Hz, as in Experiment 1. When the first epoch frequency was 72 Hz, the second epoch frequency was 90, 120, or 144 Hz. Conversely, when the first epoch frequency was 120 Hz, the second epoch frequency was 60, 72, or 80 Hz. The ‘in-between’ frequencies were those frequencies among 60, 72, 80, 90, 120, or 144 Hz that fell between the first and the second epoch frequencies. For example, when the first epoch frequency is 120 Hz and the second epoch frequency is 72 Hz, the ‘in-between’ frequencies were 90 and 80 Hz. Each ‘in-between’ frequency was presented for 12 frames in between the first and the second epoch (see Stimulus for detail).

The results are shown in Fig. 2(D) and (E). Gray squares with error bar in Fig. 2(D) represent contrast thresholds when the temporal frequency of the first epoch is 72 Hz, and those in Fig. 2(E) represent contrast thresholds when the temporal frequency of the first epoch is 120 Hz. The effects of ‘in-between’ epochs are evident when comparing the contrast thresholds of Experiment 2 with those of Experiment 1 in the same conditions. Two-way ANOVA shows that contrast thresholds significantly increase with the ‘in-between’ frequencies in both increasing ($F_{1,6} = 78.96,\ \eta = 0.93, p = 1.13 \times 10^{-4}$) and decreasing temporal frequency conditions ($F_{1,6} = 82.61,\ \eta = 0.93, p = 9.96 \times 10^{-5}$). The results show that the TTP magnitudes can be reduced by introducing ‘in-between’ frequencies, and as described above, both the bi-phasic (cyan) and Gaussian filter (yellow) models provide good fits to the results.

4.3. Experiment 3: effects of the length of ‘in-between’ frequency epochs

The results of Experiment 2 suggest that subtle manipulations of flickering patterns presented between the first and second epochs can significantly modulate TTP magnitudes. In Experiment 2, the number of ‘in-between’ frequency frames was fixed at 12 frames. In Experiment 3, we varied the length of the ‘in-between’ frequencies by adjusting the number of frames. For example, when the number of frames was one, in the transition between 72 Hz and 144 Hz, a single frame of 80, 90, and 120 Hz stimuli was presented during the in-between epoch, as illustrated in Fig. 3(A). The number of frames ranged from 0 to 13. Note that the 0-frame condition has no ‘in-between’ frames, identical to the stimulus used in Experiment 1.

Initially, we hypothesized that TTP magnitudes would gradually decrease and eventually approach an asymptote as the number of in-between frames increases, because a larger number of ‘in-between’ frames indicates a relatively gradual change in flicker frequencies between the first and second epochs. However, to our surprise, the results showed a complex pattern. The black dots in Fig. 3(B) represent empirical data. As the number of ‘in-between’ frames increased, the contrast thresholds, which is again the inverse of TTP magnitudes, fluctuated up and down considerably. The repeated-measures ANOVA showed that the effect of the number of ‘in-between’ frames is statistically significant ($F_{13,130} = 46.92,\ \eta = 0.82, p < 2 \times 10^{-16}$). It is worth noting that the contrast threshold in the one-frame condition is close to one, indicating a very weak TTP magnitude. The results suggest that TTP can be effectively eliminated by manipulating ‘in-between’ stimulus patterns, which could be beneficial for industrial purposes. For example, when the temporal frequency of a display changes to accommodate content-specific requirements (e.g. higher temporal frequency in video game), inserting a single frame of an

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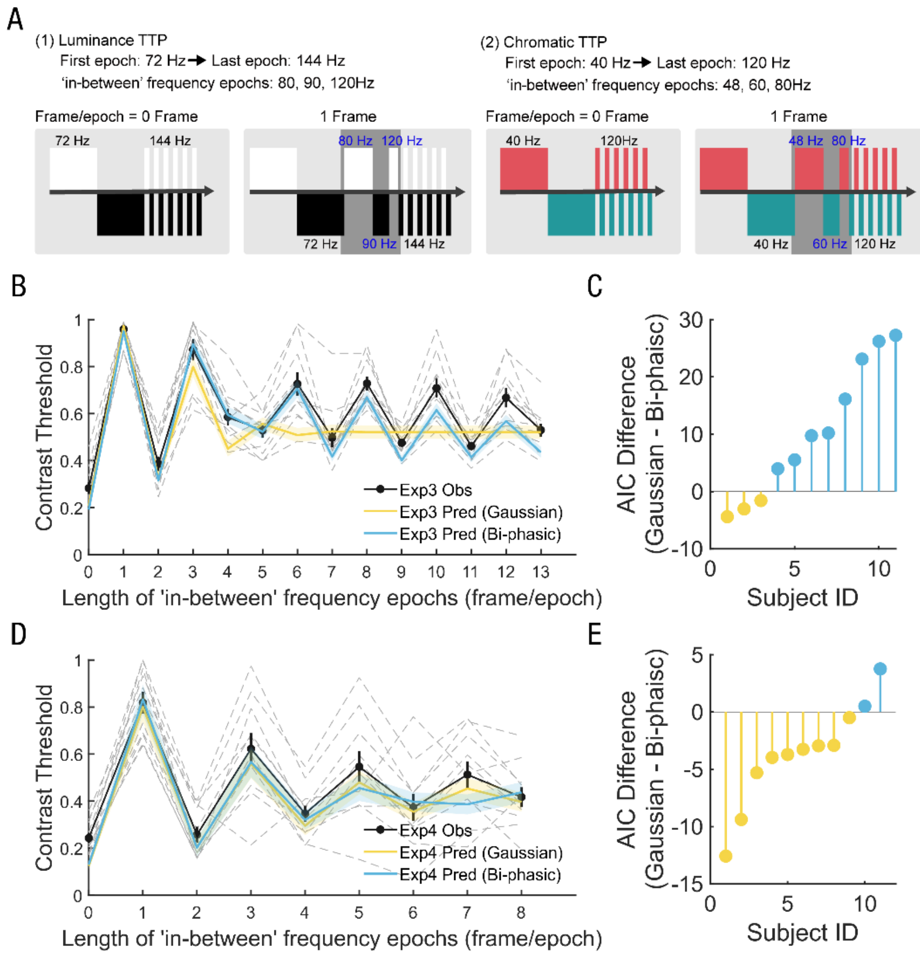

Fig. 3. The effects of the 'in-between' frequency epochs' length on contrast thresholds for luminance and chromatic TTP stimuli. (A) The luminance TTP stimuli used in Experiment 3 (left) and chromatic TTP stimuli used in Experiment 4 (right). In luminance (chromatic) stimuli, the temporal frequency transitioned from 72 (40) Hz to 144 (120) Hz. During the transition, epochs with temporal frequencies of 80 (48), 90 (60), and 120 (80) Hz were inserted. The number of inserted frames for each epoch varied from 0 (0) to 13 (8) frames, representing the different length of the 'in-between' frequency epochs. (B) Contrast thresholds measured from Experiment 3 (Black) and model predictions from Gaussian filter (yellow) and Bi-phasic filter (cyan). The x-axis represents the number of frames for each inserted frequency, and the y-axis represents the contrast threshold. Error bars drawn in black thick line indicate the mean contrast thresholds estimated at each length, while the gray dotted line plotted individuals' thresholds. (C) Results of the model comparison between the two models. The x-axis represents the participants' ID, and the y-axis represents the AIC difference for each participant. Positive value means that the bi-phasic filter model better explains observed data. (D) Contrast thresholds measured from Experiment 4 (Black) and the model predictions from Gaussian filter (yellow) and Bi-phasic (cyan). (G) Results of the model comparison between the two models. Negative values means that the Gaussian filter model better explains observed data.

'in-between' temporal frequency can efficiently mitigate unintended twinkle artifacts during the transition (see Discussion for further detail).

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The fluctuating TTP pattern was better fit by the bi-phasic filter model (Fig. 3(B) cyan) than the Gaussian filter model (Fig. 3(B) yellow). The bi-phasic filter model (Fig. 3(B) cyan) provides a better fit to the results of most participants than the Gaussian filter model (Fig. 3(B) yellow), as shown by the AIC differences (ΔAIC: AIC of the Gaussian filter model – AIC of the bi-phasic filter model) in Fig. 3(C). There were significant differences of ΔAIC between two models (see Table S3; ΔAIC: $t_{10} = 2.95,\ p = .015$. This finding is consistent with the previous studies regarding neurophysiological [23] and psychophysical [26] properties of the low-level human visual processing.

4.4. Experiment 4: effects of the length of 'in-between' frequency epochs in chromatic stimulus

In Experiment 4, we measured TTP magnitudes using equiluminant chromatic stimuli that flickered between red and green. Because the kernel of temporal filter for chromatic stimulus is known to be monophasic [15], it is expected that TTP magnitudes measured from chromatic stimuli are better explained by monophasic Gaussian filter unlike the results of Experiment 3, if TTP is indeed a product of low-level temporal filter. We designed chromatic flickering stimuli similar to those used in Experiment 3. The frequency of the first epoch was 40 Hz, the second epoch was 120 Hz, and the 'in-between' frequencies were 48, 60, and 80 Hz. We used stimuli with relatively low flicker frequency considering that the temporal sensitivity of human visual system for chromatic flicker is worse than luminance flicker stimuli [27]. We varied the number of frames for which the 'in-between' frequencies were presented (Fig. 3(A)) from 0 to 8.

Figure 3(D) shows the results. Similar to the results of Experiment 3, the contrast thresholds fluctuate as the number of the 'in-between' frequency frames increases. The size of fluctuation is statistically significant as revealed by the repeated-measures ANOVA ($F_{8,64} = 47.41,\ \eta = 0.86, p<2 \times 10^{-16}$). Despite the similar behavioral fluctuation patterns observed in Experiments 3 and 4, the model-fitting results differ significantly. For the chromatic flicker used in Experiment 4, the Gaussian filter model better explains the contrast thresholds than the bi-phasic filter model, as expected [15]. This contrasts with Experiment 3, where the bi-phasic filter model better explained contrast thresholds for luminance flicker. The preference for the Gaussian filter model in Experiment 4 is further supported by negative ΔAIC for most participants (Fig. 3(E)). Significant differences in ΔAIC were found between the two models (see Table S4; ΔAIC: $t_7 = -2.73,\ p = .021$). This might be due to the inherent characteristics of chromatic TTP perception, which could be more effectively captured by the simpler Gaussian filter model in this case.

Furthermore, we compared the shape of the temporal filters from previous studies [3,15] with the estimated filters from each experiment (Fig. 4(A) and (B)). The estimated Gaussian filter for chromatic stimuli (Experiment 4) displayed a temporal width similar to the original Gaussian filter (Fig. 4(A)). The difference observed in the tails of the filter may stem from assumptions about filter shape, as our study assumed the filter shape as Gaussian filter, unlike Burr's study. Similarly, the estimated bi-phasic filter closely resembled the original bi-phasic filter in Experiment 1-3 (Fig. 4(B)). This consistency in filter shapes with previous studies indicated the TTP is byproduct of the early-level visual processing of human vision, characterized by a Gaussian filter for chromatic stimuli, and a bi-phasic filter for luminance stimuli.

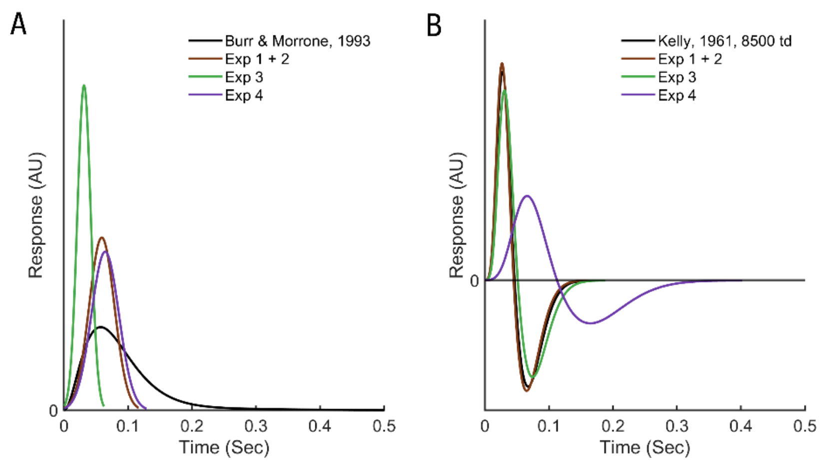

Fig. 4. The shape of the temporal filter of each model. (A) The shape of the temporal filter of Gaussian filter model from original parameters [15] (Black), average parameters from subjects in Exp1 and 2 (Green), 3 (Brown), and 4 (Purple). The x-axis represents the time of temporal filter, and the y-axis represents the filter response. (B) The shape of the temporal filter of the Bi-phasic filter model from TCSF [3] (Black), average parameters from subjects in Exp 1 and 2 (Green), 3 (Brown), and 4 (Purple).

5. Discussion

In this study, we measured the magnitude of TTP under various conditions to critically examine the mechanisms behind the TTP phenomenon. The results of Experiments 1 and 2 show that the magnitude of TTP increases as the frequency difference between the two epochs increases and decreases with a gradual transition of temporal frequencies when 'in-between' frequency frames are inserted. In Experiment 3, we found that the magnitudes of TTP unexpectedly fluctuate patten as the number of 'in-between' frequency frames increases. In Experiment 4, we observed a similar fluctuating pattern of TTP magnitude in equiluminant chromatic stimuli. Our modeling results showed that the bi-phasic filter model accounts for the luminance TTP results more effectively than the Gaussian filter model, whereas the Gaussian filter model better explains the chromatic TTP results.

Our results also resolved an inconsistency in literature. In a previous study [8], a temporal integration model with a Gaussian filter was introduced as a working model for TTP phenomenon. However, there has been converging evidence that the temporal integration in the human visual system is characterized by a bi-phasic filter [12,15]. We considered two possible explanations. First, the TTP might be a byproduct of high-level visual processing and may not reflect the properties of low-level temporal filters. Second, the TTP stimuli used in previous studies may not be sensitive enough to distinguish the type of temporal filter involved in visual processing. Our findings support the second explanation, suggesting that it is unnecessary to consider an additional mechanism beyond the established properties of low-level temporal filters. Specifically, we demonstrated that a mono-phasic Gaussian filter model cannot adequately explain the TTP magnitudes observed in Experiment 3, while a bi-phasic filter model can.

The patterns of TTP magnitudes observed in luminance (Experiment 3) and chromatic stimuli (Experiments 4) appear similar in that the contrast thresholds fluctuate as the number of 'in-between' frequency frames increases. However, there is a subtle yet critical difference between the two data patterns. In the luminance stimuli, the contrast threshold was higher when the number of frames was 1, 3, 6, 8, 10, and 12, and lower when the number of frames was 0, 2, 4, 5, 7, 9, and 11. In contrast, in the chromatic stimuli, the contrast threshold was higher when the number of frames was 1, 3, 5, and 7, and lower when it was 0, 2, 4, 6, and 8 (Table S2). The key observation here is that in the luminance stimuli, contrast thresholds are relatively high when the number of frames are odd numbers (1 and 3) initially, then switch to being high for even numbers (6, 8, 10, and 12). In the chromatic stimuli, however, the contrast thresholds remain high for odd numbers (1, 3, 5, and 7) without switching to even numbers. This switch observed in the luminance condition is predicted by the bi-phasic model but not by the Gaussian model, and it represents the key qualitative difference in the data that allowed us to distinguish between the two models. A detailed explanation regarding the relation between the shape of filters and the effects of number of 'in-between' frames on contrast thresholds is presented in the Supplement 1 (Figure S4).

For the chromatic stimulus, the contrast threshold was consistently high when the number of 'in-between' frequency frames was odd than it was even without a switch in fluctuation order. This pattern can be well accounted for by the Gaussian filter model. However, the bi-phasic filter model can also reproduce the observed pattern by elongating the positive phase of the filter. As a result, no clear qualitative distinction between the models' performance is observed in Experiment 4. Nonetheless, subtle performance differences between the two models can be captured through quantitative analysis. A model comparison using AIC revealed statistically significant differences that favored the Gaussian filter model across subjects (see Results 4). Furthermore, subject-level fitting results (Figure S3) often showed that the bi-phasic model exhibited the switch of fluctuation order at longer frame lengths (4–9 frames), driven by the inhibitory phase of the bi-phasic filter. Future studies incorporating extended 'in-between' frequency epochs or alternative forms of temporal modulation may help further clarify the temporal characteristics specific to chromatic processing.

Furthermore, our experimental paradigm offers a reliable method for estimating the temporal filter of visual processing. In the other psychophysical studies for determining the temporal filter in detection tasks, researchers estimated contrast thresholds for two pulses with opposite polarities, which presented sequentially with varying stimulus onset asynchronies [15,26,28]. In our study, the use of TTP offers an alternative approach to determining the temporal filter for each subject, yielding results consistent with previous studies, as shown in Fig. 4. Therefore, our study resolves the discrepancy between previous study and the literature on early-level visual processing by using sensitive TTP stimulus for confirming that TTP is the byproduct of early-level visual processing.

Our findings have practical implications for display technologies like Variable Refresh Rate (VRR) display, which was introduced to improve visual performance by adjusting the refresh rate with its contents property. Our Experiment 1 showed the TTP may be occurred in VRR displays, even if its temporal frequency is above CFF, highlighting the need for strategies to mitigate TTP. The previous studies suggest that the insertion of the temporal envelope which modulates the contrast gradually increase or decrease in the moment of the transition to reduce the TTP [8,9,29]. However, using a temporal envelope only works at the beginning and end of the flickering sequence to prevent the TTP, not during frequency transitions within the flickering. In contrast, our results suggest that inserting 'in-between' frequency epochs during temporal transitions (Experiments 2,3 and 4) offers a more flexible approach to reducing TTP.

Furthermore, flicker visibility in VRR displays was predicted using the elaTCSF, which modulate the Temporal Contrast Sensitivity Function (TCSF) based on the eccentricity, luminance and stimulus area [30]. Another study similarly verified that the bi-phasic filter, inspired by the TCSF of luminance stimuli, predicts the temporal luminance modulation stimulus, while a mono-phasic filter accounts for the chromatic modulation stimulus [12,15]. Building on these previous studies, we demonstrated that the bi-phasic filter model predicts the TTP on luminance, while the Gaussian filter model is more suitable for chromatic stimuli. Despite differences in

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experimental setups in prior studies, our temporal integration model robustly predicts the TTP by utilizing a specified temporal filter for each subject. Moreover, the shape of filter aligns reliably with temporal filter from previous studies, as shown in Fig. 4. Our study highlights that the proposed model robustly can reliably predict the flicker visibility across a range of temporal modulations in both luminance and chromatic contrast.

6. Conclusion

The temporal integration model we suggested here was considered to compare the performance for which type of the filter can account for TTP. However, the human visual system comprises separate processing streams, with the bi-phasic filter potentially representing the transient pathway and the Gaussian filter representing the sustained pathway [31–35]. Assuming these parallel channels, acknowledging the distinct temporal processing mechanisms for luminance and chromatic stimuli, could lead to a more comprehensive model. As observed in Fig. 4(E) and (G), some participants might exhibit minimal differences in AIC values between the two models. This suggests that they may utilize both the transient and sustained pathway rather than relying on just one of them for temporal processing. While this study focused on the individual performance of the bi-phasic and Gaussian filter models, future research could explore the potential benefits of the combined models to account for the distinct processing streams and individual variations in TTP.

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Data availability. All data can be found at [36] or upon request and all scripts of the temporal integration models and statistics are available from [37] or upon request.

Supplemental document. See Supplement 1 for supporting content.

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