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無意識單眼節律訊息處理

Unconscious Rhythmic Information Processing Under Monocular Entrainment

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Chinese Abstract

節律（rhythm）在生物系統中俯拾即是。人類神經系統亦不例外，過去有許多研究顯示大腦節律會受到外在刺激所影響，隨著相位變化而震盪（oscillate），並可見到同步化（entrainment）之現象。同時，大腦無時無刻都在處理來自外界各種訊息，然而，在眾多訊息中僅有少數能夠被主體所主觀知覺到。於是，本研究利用人類雙眼視覺之特性將節律訊息隱藏於單眼中，使此類訊息無法由受試者主觀察覺，以嘗試理解意識在節律訊息處理中所扮演之角色。實驗一之行為實驗結果顯示在 1Hz、10Hz 與 30Hz 之視覺閃爍刺激下，皆有強烈前時距效應（foreperiod effect），並無明確證據支持無意識資訊處理之現象。承接前述實驗，基於過去節律與前時距效應之眼動文獻，發現微跳視 （microsaccade）之頻率會隨著時間迫近預期刺激出現時間點而逐漸降低。實驗二即利用眼球追蹤技術作為輔助測量，搭配連續閃光抑制 （continuous flash suppression, CFS），控制前時距效應後，發現在*同步化後*雖仍然無法發現證據支持無意識資訊處理，然而在*同步化期間*透過觀察微跳視之頻率，我們發現節律性之刺激能誘導出較低之微跳視頻率之潛在證據。據此，我們推論意識可能並非處理節律訊息之必要條件。

關鍵詞：無意識資訊處理、節律、同步化、微跳視

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Unconscious Rhythmic Information Processing Under Monocular Entrainment

Yu-Hsin Lee

Abstract

The ability to unconsciously process sensory information is one of the key capabilities possessed by cognitive systems. In vision, it has been demonstrated that stable fusion can prevent conscious access to information regarding the eye-of-origin. By exploiting this lack of awareness, periodicity can be effectively hidden monocularly outside of consciousness. Meanwhile, rhythm is ubiquitous in biological systems, neural oscillation in particular has been implicated in orchestrating cognitive processes. Previous studies indicated that human subjects could be readily entrained by external periodic events, and their performance oscillated with the different phases of rhythm. However, it is still unclear to what extent and at what level of processing rhythmic entrainment can occur when the rhythmic entrainer is unconsciously presented monocularly. In the present study, we entrained our participants unconsciously with superimposed grating flickers, then probed with tilted Gabor at different phases. In experiment one, we first identified a strong foreperiod effect across the tested frequencies (i.e., 1Hz, 10Hz and 30Hz). However, results revealed no concrete evidence of entrainment. In subsequent experiment two, we adopted continuous flash suppression (CFS) to tease apart the foreperiod effect from possible entrainment. Additionally, we utilized eye-tracking as an auxiliary measurement, since reduction in microsaccade rate and oculomotor dynamics in general has been linked to reflect temporal information processing. After controlling for the foreperiod effect with experiment two. We still cannot find behavioral evidence for *post-entrainment*

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unconscious rhythmic information processing. Conversely, we observed evidence for unconscious information processing *during-entrainment*, as evidence from a local lowered microsaccade rate for periodic flicker stimulation versus non-periodic flicker stimulation. The current study demonstrated potential evidence for invisible rhythmic entrainment eliciting a similar microsaccade inhibition response as conscious stimuli. In a broader context, our results suggested that the human nervous system possesses the ability to process rhythmic information without conscious awareness.

Keywords: Unconscious Information Processing, Rhythm, Entrainment, Microsaccade

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1. Introduction

The human brain is capable of processing a vast amount of information, with only few are accessible by our conscious awareness. Numerous efforts have been devoted to uncover the unconscious processes underlying human cognition. It has been demonstrated that under stable binocular fusion, observers cannot discern to which eye each stimulus was presented, that is to say, observers had no conscious access to the eye-of-origin information(Ono & Barbeito, 1985). Taking advantage of this lack of awareness, we are able to hide rhythm outside of conscious awareness. Entrainment refers to the alignment between oscillating systems. In the context of human neuroscience, neuronal oscillation as an indispensable part of biological systems, had been linked to be involved in different cognitive functions. For instance, top-down attention (Helfrich et al., 2019), memory consolidation(Nokia & Penttonen, 2022), speech recognition (Lam et al., 2018) and motor coordination (for review, see Lakatos et al., 2019). Entrainment could involve different modalities, in vision, previous studies had revealed that during flicker stimulation, neuronal oscillation could be reliably detected in visual cortex spanning across a wide range of frequencies (Herrmann, 2001). Aside from neurophysiological investigations, further behavioral studies showed that brief exposure to periodic stimulation is sufficient for exerting behavioral performance benefit when the timing of the target is in phase with the periodicity of the stimuli (Spaak et al., 2014). Specifically, the temporally closer the target presented to the wave crest of the entrained rhythm, the higher accuracy were observed. In order to narrow down our search and better align our results to the relevant biological functions. The present study examined four frequencies from

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common frequency bands in our nervous system below the acromatic critical flicker frequency (Erlick & Landis, 1952). 1Hz was chosen to represent the delta band and the relatively long one second stimulus onset asynchrony (SOA) was comparable with the commonly used temporal cuing paradigms (Parris et al., 2012; Seibold et al., 2020; Yamashita et al., 2022). 10Hz was selected to target the alpha band, a previous studied showed that compare to other neighboring frequencies, a stronger response was observed and had been demonstrated to entrain the endogenous alpha rhythms. 10Hz stimulation was also correlated with selective attentional processes, phases of the entrained oscillation was found to predict task performance (Gulbinaite et al., 2017). 30Hz was elected to investigate the low gamma frequency bands. Lastly, the 4.6Hz was chosen not for the biological implications to our cognitive function, but rather for our high sensitivity to this specific temporal frequency. According to the stelaCSF model (Mantiuk et al., 2022), the authors built a comprehensive function that predict human contrast sensitivity using data from previous contrast sensitivity studies, and we took advantage of the model and determined that 4.6Hz to be the most sensitive given our experimental configuration.

To provide more evidence, we also employed eye-tracking as an auxiliary measure, to probe evidence of unconscious rhythmic information processing. Microsaccade as one of the fixational eye-movement has been linked to reflect covert attention and extraction of meaningful task related information (Engbert & Kliegl, 2003; Krauzlis et al., 2017; Lv et al., 2022; Vetter et al., 2019). In the context of temporal prediction, previous studies had shown that the frequency of microsaccade was correlated with the conditional probability over time, reflecting the temporal orienting of observers, under auditory cuing(Abeles et al., 2020), visual cuing(Amit et al., 2019; Tal-Perry & Yuval-Greenberg, 2020) and even cuing using tactile stimuli

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(Badde et al., 2020). Specifically, the amount of microsaccade would gradually decline as time progressed toward the next predicted onset. This inhibition of microsaccade was hypothesized to aid perceptual stability, since microsaccade initiated around target onset impair successive target detection (Martinez-Conde et al., 2013). Here, we hypothesized that if our flicker stimulation did successfully entrain our observers, we should be able to observe similar pattern of saccadic suppression.

We also assessed the potential level of processing of unconscious rhythmic information in our visual system by manipulating the eye-congruency. If the processing level is relatively low, the entrainment effect should only be observable in conditions in which the eye-of-entrainment and the eye-of-target-presentation are matched (i.e., congruent condition), but not for the incongruent condition.

In the present study, we investigated two different aspects of rhythmic information processing (RIP) outside of conscious awareness. In experiment one, we took advantage of the lack of eye-of-origin information in our visual perception, presenting periodic flickers in one eye along with identical-looking but temporally scrambled flickering distractors on the other eye to investigate the unaware aspect of RIP. In other words, flickering was always conscious, only the periodicity was hidden from conscious access. In Experiment two, we used continuous flash suppression (CFS)(Tsuchiya & Koch, 2005) to investigate the unconscious aspect, under such suppression, not only the periodicity was hidden, the flickering stimulation was entirely non-visible for the unconscious trials. To wrap up, for experiment one, we expect to find better behavior performance when the target was presented in phase with the entrained rhythm; for experiment two, we expect similar behavioral performance profile to experiment one along with stronger microsaccade inhibition for periodic stimulations.

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2. Materials and Methods

2.1 Observers

All observers were recruited from public Facebook groups, members made up of primarily students and alumni of National Taiwan University, National Tsing Hua University, National Taiwan University of Science and Technology and National Chiao Tung University (was officially renamed as National Yang Ming Chiao Tung University during the writing of the present thesis). All observers were naïve to the purpose of the study, gave written informed consent before participation and were compensated with participation fee. For experiment one, 85 observers were recruited, 17 out of 85 failed to complete the experiment. For experiment two, 36 observers were recruited, 27 observers completed both behavior and eye-tracking sessions without technical issue, two additional observers were excluded for analysis, due to imbalanced trial responses.

2.2 Stimuli

For entrainment, the superimposed Gabor patch was created by stacking two 50% Michelson contrast Gabor patches together (i.e., GreatingStim in psychopy2), with one of the Gabor rotated 90 degrees clockwise. Edge smoothing was achieved by applying Gaussian blur on the border of the Gabor, creating a circular grating-like patch. On the other hand, the target used for the orientation discrimination task was one single full contrast Gabor patch, rotating either clockwise or counter clockwise by one degree. All stimuli were of the same size, 7.13 degrees in diameter and present for 4.17ms.

2.3 Experiment One

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2.3.1 Practice Trials

To help the participants familiarize themselves with the procedure, they were given 20 practice trials prior to the main experiment.

2.3.2 Main Experiment

Utilizing the dichoptic viewing setup, we presented two different streams of flickers separately to the two eyes of the observers. Namely, the periodic and non-periodic stream. In experiment one, we focused on the following three frequencies, 1Hz, 10Hz and 30Hz. Importantly, the only difference between periodic versus non-period condition was the temporal regularity, that is, the number of stimuli was identical across the two streams to maintain consistent total energy for both eyes. As an example, for all 10Hz conditions, in average, the observers will receive 10 flickering stimulations every second, the only difference was whether the stimulation was flickering periodically (i.e., *Periodic*) or temporally scrambled (*Non-periodic*). Each trial begins with flicker entrainment of different length (two seconds, three seconds or four seconds). After entrainment, we probed our observers at three different time points. For the *In Sync* condition, the target was presented in sync with the previously entrained rhythm. For example, under 1Hz entrainment, the target was presented exactly one second after entrainment ended. To make the target timing comparable across frequencies, the stimulus onset asynchrony (SOA) for the target was determined using the following formula *entrained frequency* timing ratio.* For the *Premature* condition, the SOA from the end of entrainment to the target onset was set to 60% of the entrained SOA. For instance, for all 10Hz conditions, the *Premature* SOA was 60ms (i.e., 100*0.6). For the *Delay* condition, the timing ratio was set to 160% of the entrained SOA. As an example, for 30Hz entrainment under *Delay*

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timing, the SOA was 53.33ms (i.e., 33.33*1.6). All targets and superimposed Gabor patches used in the present study were flashed for a duration of one frame in a 240Hz display, lasted 4.17ms. After target presentation, the participants had to make a speeded response indicating the orientation of the target within 1500ms, no response was collected if exceeding this time limit (see figure 1 for trial structure).

Every observer in experiment one was randomly assigned to one frequency of entrainment, and conducted a total of 288 trials. All factors were completely crossed, number of trials for the conditions were counterbalanced, and the trial sequence was randomized for every subject. The session typically lasted for about 60 minutes, with self-paced breaks implemented mid-experiment.

2.4 Experiment Two

2.4.1 Practice Trials

Both sessions of experiment two began with practice trials. For the first session, 20 trials were given to the observers to help familiarize themselves with the task. The practice portion for the second session concluded once two reversals had been achieved on both staircases across all four conditions.

2.4.2 Main Experiment

2.4.2.1 Session One. In the previous experiment, we failed to find evidence for unconscious rhythmic information processing using our *end-of-trial* RT measures. Thus, we aimed to investigate potential *within-trial* differences. Specifically, the first aim for experiment two was to compare the difference in breaking contrast threshold for periodic versus non-periodic flickers across our frequencies of interest under CFS (see figure 2 for trial structure). Mondrian masking was always presented on the dominant eye determined using hole-in-the-card method, and the periodic or

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non-periodic flicker was presented on the non-dominant eye. To prevent premature breakage of stimuli, each trial began with an early CFS mask onset. Being entrained by the flickering gratings, the observer had to report awareness during trial by pressing the b key on the keyboard whenever they observed the flicker. The contrast was adjusted on a trial by trial basis following the modified PEST (Parameter Estimation by Sequential Testing) procedure (see Staircase Procedure for a detailed explanation). Frequency wise, aside from the previously investigated 1Hz, 10Hz, and 30Hz, we introduced a new frequency of 4.6Hz. Utilizing the stelaCSF function (Mantiuk et al., 2022), the authors provided a simulation model based on previous contrast sensitivity literatures, to make predictions about the contrast sensitivity under different temporal and spatial properties of the stimuli. Here we took advantage of the stelaCSF simulation, determined that 4.6Hz to be the most sensitive given the spatial frequency of 5 cpd. The second aim was to estimate the contrast threshold that can be used in the next session (see section 2.4.2.2). In addition, we also increased the entrainment duration from 2±1 to 8±1, as this increased trial length should provide more temporal cue for human rhythm tracking system to pick up.

Within-subject block design was implemented for experiment two. That is, all observers were entrained under all four frequencies, with trials from the same frequency blocked together. To counter the potential sequential and carryover-effect inherent to block design. Balanced Latin Square was used across observers. Notably, although Balanced Latin Square was implemented *across* observers, identical sequence of stimulation was used for every given observer for both sessions. Put differently, for an observer assigned to 4.6Hz, 10Hz, 30Hz and 1Hz, this sequence will be used for both sessions, ensuring consistent sequential effect. Within each block, trials were randomized.

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2.4.2.2 Session Two. In addition to investigate the within-trial unconscious rhythmic information processing. In session two, we also aimed to further examine the possible confound resulting in the null results, we identified foreperiod effect (i.e., the SOA differences among the Target Timing conditions) as a possible major contributing factor. We manipulated the CFS masking duration to control for the foreperiod effect within each frequency. Specifically, we extended the duration of masking beyond the end of entrainment, so that regardless of the synchrony of the target to the entrained rhythm, the foreperiod could be held consistent (see figure 3 for visualization). As an example, 1Hz In Sync condition in experiment one gave the observers 1000ms worth of foreperiod, now in experiment two, by extending the Mondrian masking for an extra 400ms past the end of entrainment, now the foreperiod was effectively 600ms (see table 1 and table 2 for comparison). Similarly, 1Hz Delay condition before masking extension, had a foreperiod of 1600ms, by extending the masking for an extra 1000ms, the foreperiod in experiment two was reduced to the same degree as 1Hz with In Sync target timing (i.e., 600ms) (see figure 4 for trial structure).

Our objective was to examine the unconscious aspect of rhythm perception. To this end, we utilized the contrast threshold estimated through the modified one up one down PEST procedure from the first session, and carried this final estimated threshold over to the second session for presenting the flickers at near-threshold levels. This approach aimed to strike a balance between the strength of stimulation and the breaking rate. In the present session, eye-tracking was added to monitor oculomotor dynamics during entrainment. The procedure was identical to session one, except that at the end of entrainment, the observers had to conduct a Gabor orientation discrimination task. In other words, the observers had to not only indicate the

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awareness during trial but also made speeded response indicating the orientation of the target at the end of every trial. In an effort to refine the procedure for eye-tracking, each trial was initiated with a three-second period consisting solely of the fusion aid and fixation dots. This was then followed by a buffering period of 100 milliseconds to allow the eye-tracking system to process the data efficiently.

2.4.3 Staircase Procedure

Due to the nature of this exploratory study, in the first session of experiment two, a modified one up one down PEST procedure was chosen for threshold estimation, to take advantage for its higher tolerance for sub-optimal initial value and step sizes (Leek, 2001). For the present study, the contrast of the entraining flicker reduced in half after every reversal was reached. In addition, a full repeat (i.e., revert back to using larger step sizes) of the step sizes was also implemented as a preventative measure for premature anchoring to local minima or maxima. For a similar reason, we used two initial value of 0.3 and 0.6 instead of just one, ran two separate sub-staircases, providing additional anchoring points to better aid orienting to the final contrast threshold. The final contrast threshold was estimated by calculating the mean of the last two reverse points of the two sub-staircases (i.e., two from the sub-staircases started with 0.3 contrast, another two from the sub-staircases started with 0.6 contrast).

2.5 Apparatus

2.5.1 Script and Software Interfacing

Stimuli presentation scripts used in this study were programmed under the Python programming language (Python version 3.8). In order to obtain a high temporal precision, all texture functions were called from the Psychopy library (Peirce

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et al., 2019), with sizes set following the *power-of-two rule* to avoid additional background scaling procedures performed by the operating system. In terms of hardware interfacing, keypress and related Human Interface Device (HID) implementations were called from the Psychtoolbox Library (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007), to ensure proper compatibility and precision. To accurately and consistently collect responses from all observers, Zowie Celeritas II gaming keyboard with PS2 connector and linear switches was chosen. As the PS2 interface is considered superior to the Universal Serial Bus (USB) due to its deliberate design choice of actively interfering with CPU processes, rather than relying on pooling as in USB.

2.5.2 Hardware

2.5.2.1 Personal Computer. A custom PC running Windows 10 Pro was used to run all of the experiments. The Discrete NVIDIA RTX 2080 super graphics card slotted in the x16 PCIe slot of the motherboard was used to output video signals to two separate screens. One for stimuli presentation, another for experimenter monitoring. For stimuli presentation, a 24.5-inch 240Hz MSI OPTIX MAG Gaming Monitor running at native 1920*1080 resolution connected via a HDMI 2.0 compliant port and fiber-optic cable was used. An additional display(1920*1080@60Hz) was attached for monitoring purpose. Monitored using the Windows built-in task manager on a separate PC during preliminary performance assessment, while running our custom presentation scripts, the task manager reported minimal multi-core task allocation, implying that single core performance should be of highest priority for our custom hardware. That is why the Intel i9 11900K was the CPU of choice.

2.5.2.2 Dichoptic-Viewing Device. A custom-made dichoptic viewing device

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was used to constrain the observer's field of view. Light absorbing agents were coated on the inner compartment to minimize internal reflections. Additional optical lenses were also used to facilitate binocular fusion.

2.5.2.3 Eye-tracking Set-up. The Eyelink 2000 by SR research with 25mm wide angle lens in a tilted position designed for binocular head supported recording was used to collect eye-tracking data. Calibration was conducted before data collection for each block using a custom 9 points square calibration matrix (10.03° by 10.03° in length) with the calibration targets spread evenly in the visual field of the dominant eye. The calibration and validation procedure will only terminate after < 1° of discrepancy between the two was obtained.

2.5.2.4 Environment. For experiment one, data was collected inside a sound attenuating chamber to reduce both visual and audio distractions. The observers were sat comfortably in a slightly dimmed room and the temperature was controlled (at about 24 degrees Celsius) to ensure comfort and consistent LCD pixel response time. In addition, the monitor was turned on and preheated by running custom scripts at least 30 minutes prior to data collection, this procedure was conducted to ensure consistent pixel GtG performance. For experiment two, data was collected in a quiet room with the only light source being the backlight of the stim-presenting PC monitor.

2.5.3 Instructions

Throughout this study, the observers were instructed to maintain fixation whenever the fixation dots were present and try to maintain fusion by keeping the fusion aids merged, but free to blink at any time they deem necessary.

For experiment one, the observers were instructed to press the arrow keys as fast and as accurate as possible to indicate the orientation of the target Gabor patch. For

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session one of experiment two, the observers were instructed to press the b key on the keyboard if any part of the flickering stimuli was visible. For session two, similar to previous session, the observers were instructed to not only report visibility of the flicker by pressing the b key, but also need to perform the Gabor orientation discrimination task by pressing the arrow keys at the end of every trial.

2.5.4 Debriefing Procedure

After completing the main experiment, debriefing will be given to the observers. They will be asked the following questions in the order shown below: 1. Please roughly describe how the questions(trials) was organized and which key(s) should be pressed under each condition. 2. Did you employ any strategy during the experiment? If so, please describe the strategy in as much detail as possible. 3. Did you observe any type of regularity throughout the experiment? 4. In your opinion, what do you think this experiment is about? 5. Did you experience any unfusing during the session? Only after completing the verbal debriefing. The observers were informed about the purpose and manipulations of the present study. Question one and two were designed to catch the observers that failed to follow instructions. Question three was implemented as a check to make sure that the rhythm was not being noticed in any capacity. Notably, this question was necessary since unlike experiment two, in which observers had to indicate their awareness for every trial. The rhythm-hidden-stimuli-visible design of experiment one relied on this question as a mean of subjective report, to screen out “breaking” observers. To avoid response biases, wording for the third question was purposely vague, asking about the *regularity* rather than rhythm specifically. Question four was also designed to catch the “breaking” observers by pushing the participants to guess the purpose of this study.

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Finally, the last question was implemented to screen out the poor fuser.

2.6 Data Analysis

2.6.1 Experiment One Behavioral Data Analysis

All data for experiment one was analyzed using custom scripts implemented in R (R Core Team, 2021). Reaction time was first fitted with linear mixed effect model (LMM) using the lem4 package without aggregation, then conducted ANOVA for the fitted model. Adhering to our hypothesis, the fitted model incorporated three fixed effects, namely congruency, target timing and entrained frequency, observer was integrated as a random slope to allow the baseline performance to very across observers. Pair-wise comparisons were conducted using the emmeans package (Lenth, 2021).

2.6.2 Data exclusion Criteria and Procedure

For reaction time, two exclusion criteria were determined *a-priory*. Within each observer, RT data was first z-transformed, trials with larger than 2 or smaller than -2 z-score were excluded from the analysis. To exclude all data from a given observer, in addition to the ones flagged as not following instruction during debriefing (see, debriefing procedure for more detail). We were still concern that some of the observers were not sufficiently attentive to the assigned task and identified two major characteristics, namely, high number of misses and low catch trial accuracy (i.e., targets with 45 degrees tilt instead of the one degree for regular trials). Thus, those with missed trials larger than 2 SD away along with lower than 2 SD catch trial accuracy were removed from analysis.

2.6.3 Experiment Two Behavioral Data Analysis

2.6.3.1 Session One. The goal for the first session was to estimate the threshold

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for periodic and non-periodic flicker stimulation. The final contrast threshold was estimated by calculating the mean of the last two reverse points of the two sub-staircases. After obtaining the threshold, the threshold was fitted to an LMM with two fixed effects (i.e., Periodicity and Entrapment Frequency), observer was incorporated as random factor to account for individual difference.

2.6.3.2 Session Two. Similar to the RT analysis in experiment one, the RT data was analyzed using mixed effect modeling. In which the raw data was fitted using LMM model with fixed effect including congruency, target timing and entrained frequency, and a random effect of observer. Pair-wise comparison was conducted to compare all target timing*congruency combinations within each entrained frequency.

2.6.4 Eye-Tracking Data Analysis

2.6.4.1 Microsaccade Detection and Pre-processing. Microsaccade was detected using velocity-threshold based algorithm proposed by Engbert & Kliegl (Engbert & Kliegl, 2003), with the threshold multiplier value set to five. In other words, only saccade velocity exceeding five standard deviation away was included as candidates for further analysis. To further prevent false positives, we imposed a 50ms minimal spacing between successive microsaccade detection (Denison et al., 2019). Blinks were parsed with standard algorithm provided by SR research, however, after visual inspection on the trial progression, some post-blink and pre-blink artifacts was not properly removed, to further ensure data quality, a 200ms pre and post blink microsaccade detection rejection was added (Dankner et al., 2017; Denison et al., 2019). Since binocular data was acquired, in additional to velocity-based criteria, the binocular data was also compared as Hermens in the 2015 article (Hermens, 2015) suggested that in order to avoid type I error, only microsaccade detected on both eyes were included in the analysis. Amplitude wise, in the present study, only saccade with

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amplitude < 1° were included in the analysis.

2.6.4.2 End-of-Entrainment Microsaccade Frequency Analysis. After controlling for the amount of foreperiod using CFS, the aim for the present analysis was the same as experiment one, to examine evidence of unconscious rhythmic information processing using microsaccade frequency instead of only behavioral measures. We planned to compare difference in microsaccade frequencies between different entrainment to target synchrony (i.e., target presentation timing relative to the entrained rhythm). The steps for the present analysis were as follows. Microsaccade data was first binned in a series of 50ms (Tal-Perry & Yuval-Greenberg, 2020) time bins without additional sliding window smoothing. For each time bin, we calculated the microsaccade frequencies separately under different conditions and pooled all the time bins between the *end of entrainment* to the *target onset* together and ran t-tests with Bonferroni multiple comparisons adjustment, on all combinations of *Entrained Frequency * Target Timing*.

2.6.4.3 During-Entrainment Microsaccade Frequency Analysis. In contrast to the previous analysis that focused solely on the end-of-entrainment microsaccadic events, we now look for microsaccade frequency differences *during entrainment*. The time series was first normalized with linear interpolation to reflect different entrainment length. After normalization, we proceeded on binning the microsaccade dataset into 150ms time bins, then smoothed the entire time series with 1ms sliding window. After smoothing, for the first analysis, we first aggregated our data by observer, performed a paired t-test on overall microsaccade rate within the entrainment period, focusing on the comparison between *nonperiodic unconscious* against *periodic unconscious*. The second analysis turned to look at potential difference at local level, instead of performing one single t-test on by-observer

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microsaccade rate, in the second analysis, we opted to conduct a series t-tests for all time points within the entrainment period.

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3. Results

3.1 Experiment One

In experiment one, the observers were instructed to press the corresponding key to indicate the orientation of the target Gabor patch. Reaction time (RT) were collected for analysis. Adhering to our hypothesis, we fitted a linear mixed effect model (LMM) incorporated three fixed effects, namely eye congruency, target timing and entrained frequency. In terms of the random effect, the observers were integrated as a random slope in the model, and ran analysis of variance (ANOVA) using RT as a dependent variable. Results were shown in Table 3. The analysis revealed, two out of three two-way interactions were significant, the first one was between eye congruency and entrained frequency $F(2, 49936.16) = 16.86$, $p < .01$, $\eta p^2 = .00$. The other two-way interaction was between target timing and entrained frequency $F(4, 49936.16) = 12.05$, $p < .01$, $\eta p^2 = .00$. Finally, main effect of target timing $F(2, 49936.16) = 122.89$, $p < .01$, $\eta p^2 = .00$ and entrained frequency $F(2, 97.98) = 122.89$, $p < .01$, $\eta p^2 = .13$, were both significant. As indicated by partial eta squared, our results suggested that there was a strong effect driven by frequency. Crucially, in light of the two-way interactions, we proceeded to conduct pair-wise comparisons to further investigate the interactions. The results were shown in figure 5, we observed, besides the strong frequency effect, a clear downward trend was present over the three target timings for 10 Hz and 30Hz but not for 1 Hz. Our interpretation for the absence of the downward trend was that compare to the relative short time window for 10Hz (mean = 106.67 ms) and 30Hz (mean = 35.55 ms), the mean time window for 1Hz stimulation was

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1066.67 ms, which was at least 10 times longer than the other two conditions, resulted in the RT performance to calling. As an interim conclusion, instead of the hypothesized *in sync (i.e., entrainment)* performance benefit, we observed a strong foreperiod effect. Here in experiment one, we found no evidence for unconscious rhythmic information processing.

3.2 Experiment Two

There were two sessions for experiment two. The first session was used to estimate the contrast threshold using PEST procedure that only required the observer to indicate awareness of the flicker entrainment under CFS. For session two, the observers had to not only indicate awareness mid-trial but also conduct Gabor orientation discrimination task at the end of every trial. Session one was purely behavioral, while eye-tracking was added for session two.

3.2.1 Session One Results

In this session, we first examined the staircase estimated threshold across frequencies and periodicity. The linear mixed effect model fitting revealed the following (see figure 6). For fixed effects, we found no two-way interactions between entrainment frequency and target timing, but significant effects among the frequencies. Specifically, when comparing 10Hz to the reference level 1Hz (β = -0.21, *SE* = 0.038, *df* = 182, *t* = -5.6, $p < .01$), 30Hz compared to 1Hz (β = -0.25, *SE* = 0.037, *df* = 180, *t* = -6.80, $p < .01$), and 4.6Hz compared to 1Hz (β = -0.13, *SE* = 0.037, *df* = 182, *t* = -3.51, $p < .01$), suggesting a strong frequency of entrainment effect (see table 4). However, no statistically significant fixed effect was found when comparing periodic versus non-periodic flickers (β = -0.0081, *SE* = 0.037, *df* = 182, *t* = -0.22, *p* = 0.82). Taken together, the results suggested that although frequency effect was present, still

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no evidence for the within trial unconscious rhythmic information.

3.2.2 Session Two Results

3.2.2.1 Behavior Results. The behavioral measures in the current session were used as a check to assess the effectiveness of CFS foreperiod control. Specifically, if the downward trend were to be eliminated with CFS, this would support our hypothesis that what we observed in experiment one was genuinely driven by the duration difference in foreperiod. Linear mixed effect results revealed no significant fixed effect across the board (see figure 7 and table 5). This suggested that our extended CFS masking did control the foreperiod to a similar degree across target timings.

3.2.2.2 End-of-Entrainment Microsaccade Frequency Analysis. The present analysis was aimed to examine the microsaccade frequency form the end of entrainment to the target onset. All time bins fell within the specified range of unconscious correct trials were pooled together to perform a series of t-tests on all combinations of frequency*target timing combinations. Results revealed none of the pairs to be statistically significant (see figure 8 and table 6). This result was consistent with the behavior results presented in the previous section, no evidence for unconscious rhythmic information to be found.

3.2.2.3 During-Entrainment Microsaccade Frequency Analysis. Here, we redirected our focus to examine potential difference in microsaccade frequency *during entrainment*. We first carried out an area under the curve (AUC) calculation and conducted a t-test within the time window of entrainment, concentrating on the unconscious periodic versus the unconscious non-periodic condition. The first analysis we conducted was to test throughout the entrainment period, after aggregated

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by observers, were there any difference among the two. The results revealed no statistical difference $t(24) = 0.95$, $p = .35$ between unconscious periodic versus unconscious non-periodic entrainment. As illustrated in a past study (Dankner et al., 2017), the effect of temporal regularity on microsaccade inhibition might not be readily observable throughout the trial progression. Thus, we proceed by conducting local analysis, performing t-tests along the time series during entrainment for every time point. We discovered a portion of the tests were significant (see figure 9). For unconscious periodic versus unconscious non-periodic comparisons, we observed a total of 285 comparisons to be statistically significant. In terms of the distribution, we found all comparisons clustered beyond the 50% mark (i.e., second half) of the entrained duration. In addition to individual t-tests, we also conducted continuity check for the significant comparisons (see table 7). We found a maximum of 75 continuous comparisons to be significant.

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4. Discussion

4.1 Experiment One

In experiment One, we aimed to use offline behavioral measures to assess the presence of unconscious entrainment, and our result failed to provide positive evidence for such entrainment. Instead, we observed shortening in response time as the time window elongated, and identified the present results to be in line with the foreperiod effect literature (Niemi & Näätänen, 1981).

There are four working hypotheses that might account for the null results. The most readily apparent proposition is that our binocular presentation simply disrupted the regularity outright, as monocular input was sent to both lateral geniculate nucleus (LGNs) and to respective hemisphere for further processing. Which implies that both hemispheres will simultaneously receive stimulation from both periodic and non-periodic flicker streams. It is possible that the non-periodic stream nullifies the effect of entrainment induced by the periodic stream, resulted in the null findings. To support the aforementioned hypothesis, in a 2014 study (Spaak et al., 2014), the authors employed a fully conscious and spatial cuing entrainment paradigm. Using visual entrainment, they observed similar behavioral performance profile as our present study. Notably, they presented periodic and nonperiodic flickers to separate visual hemifields, rather than assigning each flicker type to a separate eye. Verified using magnetoencephalography (MEG), their results showed that this separate hemifield approach ensured, in terms of the early visual areas, only one hemisphere (i.e., the hemisphere receiving periodic flicker) was entrained by the periodicity. In

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light of their results, it is possible that in order for the rhythm information to propagate downstream eliciting behavioral benefit, the temporal regularity needs to be sent to and processed in one single hemisphere. The second possibility is that the rhythm information did survived under our paradigm, but given the presence of the strong foreperiod effect, behavioral measures might not be sensitive enough to capture the typically weaker and sometimes unstable unconscious effect. A recent study (Graaf & Duecker, 2022) expressed similar view, identifying low sensitivity in behavioral measures might have caused the null results. Further experiment can be conducted using more fine-grained probing interval, that is, instead of probing at three different timing (i.e., Premature, In Sync and Delay) as in the present experiment. A much denser probing interval might help better capture the relatively fine-grained difference reflecting the unconscious effect. Another potential reason for the null results for experiment one was that the present study opted for an orthogonal design. In other words, after entrainment, the participants were instructed to perform a Gabor orientation discrimination task, which is orthogonal to the aim of the study. Although orthogonal design was common and widely used in conscious time perception studies. It is still theoretically possible that this temporally irrelevant task simply failed to capture the weaker unconscious target timing effect that we were after. Lastly, in the present experiment, we tested three candidate frequencies from each frequency bands. Although these frequencies were highly biologically relevant, correlated with various cognitive functions. However, in terms of sensitivity, they might not be the most entrainment-ready frequencies. This conclude the four working hypotheses to account for the null results in experiment one.

4.2 Experiment Two

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4.2.1 Session One.

In session one, we aimed to find evidence for *during entrainment* unconscious processing. We compared contrast threshold of periodic versus nonperiodic flicker stimulation for all four frequencies, but found no statistical difference between periodic versus nonperiodic stimulation. However, we identified a strong frequency effect, that is, the higher the temporal frequency, the lower the estimated threshold. The outcome diverged significantly from prior research wherein spatial-temporal contrast sensitivity, has been observed to exhibit a concave relationship, denoting a decline in sensitivity with the increase of temporal frequency. (Mantiuk et al., 2022; Robson, 1966; Snowden et al., 1995). Our interpretation for the inconsistency is that the effect we observed were confounded by events occurring per unit time. The lower contrast threshold for 30Hz can be attributed to the sheer volume of flickers per second, increasing the probability for a given trial to break. Put simply, compare to 1Hz, 30Hz stimulation contained 29 more events per second to be detected. Potential solution is to attenuate the flicker's transience. Substituting the abrupt, transient onset flicker employed in the current study with a temporally modulated grating that features a more gradual transition could be beneficial. The incremental transition could foster greater flicker uniformity, rendering the events per unit time less noticeable to observers.

4.2.2 Session Two.

In the present session, we set out to achieve two goals. The first goal was similar to experiment one, we examined the *end-of-trial* unconscious entrainment effect. After holding foreperiod constant using CFS, the results from behavioral experiment and microsaccade rate were in agreement, either of the analysis found

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evidence for unconscious information processing. The results for this session validated our hypothesis that the RT reduction in experiment one across frequencies was driven by different amount of foreperiod. That is why after controlling for the amount of foreperiod in this session, RT difference among the target timings were leveled.

The second goal was to examine evidence for *during-entrainment* unconscious rhythmic information processing. To do so, we calculated the microsaccade rate during the entrainment period. Through local analysis, we found stronger microsaccade inhibition (i.e., lower microsaccade rate), for the periodic compared to the nonperiodic flicker when the trials were unconscious. The results were in line with numerous conscious studies (Abeles et al., 2020; Amit et al., 2019; Badde et al., 2020; Tal-Perry & Yuval-Greenberg, 2020), in which all stimuli were consciously perceived and presence of stronger microsaccade inhibition was correlated with presence of temporal regularity. Our results suggests that, although the evidence is limited, potential information processing is present during unconscious entrainment.

Consequently, there appears to be a contradiction in the results derived from the two sessions. In session one, no evidence was found to support an end-of-trial entrainment effect, whereas there was a discernible difference in local microsaccade rates during entrainment. Our interpretation of these seemingly inconsistent finding posits that the discrepancy may be attributes to the potent suppressive power of the CFS Mondrian, which inhibits the continuation of the oscillation, resulted in the null results in session one, in which only end-of-trial effect was examined. However, this suppression does not preclude information processing altogether. That is why local during-entrainment microsaccade difference can still be present under CFS. In other words, we hypothesize that in order for the stronger microsaccade inhibition to be

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observed in periodic stimulation, the continued presence of the flicker is necessary for this effect to survive the suppression from CFS. Another related possibility for the null findings could be attributed to the competitive entrainment from the 10Hz Mondrian mask. The mask was intentionally designed to be both dynamic and salient to suppress our awareness toward the transiently presented stimuli on the other eye. It is probable that this strong masking technique competitively entrained our nervous systems, eventually nullifies the target timing effect.

As a closing remark, besides uncovering potential positive evidence for unconscious rhythmic information processing, this study holds distinction from a methodological perspective. The present study is to the best of our knowledge, the first study to investigate microsaccade dynamics under CFS masking, and we demonstrated that microsaccade could still be detected under the fast changing and salient masking procedure. It is our aspiration that this attempt may also lay the groundwork for forthcoming methodological advancements.

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Tables

Table 1

Experiment One Target Timing Table

Target Timing / Entrainment Frequency	Premature (0.6x)	In Sync (1.0x)	Delay (1.6x)	Further Delay (2.6x)
1Hz	600	*1000*	1600	*N/A*
10Hz	60	100	160	*N/A*
30Hz	20	33.33	53.33	*N/A*

Note. Time window measured in milliseconds (ms). The Target timing is referring to the time window between the time between the end of entrainment to the onset of target

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Table 2

Experiment Two Time Window

Target Timing /Entrainment Frequency	Premature (0.6x)	In Sync (1.0x)	Delay (1.6x)	Further Delay (2.6x)
1Hz	600	600	600	600
4.6Hz	130.43	130.43	130.43	130.43
10Hz	60	60	60	*60*
30Hz	20	20	20	*20*

Note. Time window measured in milliseconds (ms). The Target timing is referring to the time window between the time between the end of entrainment to the onset of target.

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Table 3

Experiment One Reaction Time Linear Mixed Effect ANOVA Table

Item	Sum.Sq	Mean.Sq	NumDF	DenDF	*F*	*p*	ηp²
Eye Congruency	0.05	0.05	1	49,936.16	2.52	.113	0.00
Target Timing	4.64	2.32	2	49,936.35	122.89	< .001***	0.00
Entrainment Frequency	0.28	0.14	2	97.98	7.45	.001***	0.13
Eye Congruency: Target Timing	0.01	0.00	2	49,936.16	0.22	.802	0.00
Eye Congruency: Entrainment Frequency	0.64	0.32	2	49,936.15	16.86	< .001***	0.00
Target Timing: Entrainment Frequency	0.91	0.23	4	49,936.33	12.05	< .001***	0.00
Eye Congruency: Target Timing: Entrainment Frequency	0.12	0.03	4	49,936.16	1.55	.184	0.00

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Table 4

Experiment Two Session One Linear Mixed Effect Summary Table

Fixed Effects	Estimate	*SD*	*df*	*t*	*p*
(Intercept)	0.50	0.04	61.84	12.51	< .001***
Periodicity Periodic	-0.01	0.04	182.00	-0.22	.825
Entrainment 10Hz	-0.21	0.04	182.00	-5.60	< .001***
Entrainment 30Hz	-0.25	0.04	182.00	-6.80	< .001***
Entrainment 4.6Hz	-0.13	0.04	182.00	-3.51	< .001***
Periodic:10Hz	0.07	0.05	182.00	1.28	.201
Periodic:30Hz	0.05	0.05	182.00	1.06	.292
Periodic:4.6Hz	0.03	0.05	182.00	0.65	.517

Note. The estimates are LMM model estimated (Michelson) contrast threshold.

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Table 5

Experiment Two Session Two Reaction Time Linear Mixed Effect Summary Table

Item	Estimate	*SD*	*df*	*t*	*p*
(Intercept)	0.67	0.03	124.80	25.10	< .001***
Congruency Incongruent	0.00	0.01	7,235.35	0.23	.820
Target Timing Further Delay	-0.00	0.01	7,234.48	-0.09	.930
Target Timing In Sync	0.00	0.01	7,234.20	0.41	.680
Target Timing Premature	-0.01	0.01	7,234.67	-0.88	.380
Entrainment:4.6Hz	0.01	0.04	125.93	0.28	.780
Entrainment:10Hz	0.06	0.04	125.81	1.61	.110
Entrainment:30Hz	0.09	0.04	127.68	2.45	.020*
Congruency Incongruent: Target Timing Further Delay	0.01	0.02	7,234.55	0.33	.740
Congruency Incongruent: Target Timing In Sync	-0.01	0.02	7,234.44	-0.86	.390
Congruency Incongruent: Target Timing Premature	0.02	0.02	7,234.60	1.00	.320
Congruency Incongruent: Entrainment 4.6Hz	-0.00	0.02	7,235.52	-0.08	.940
Congruency Incongruent: Entrainment 10Hz	0.02	0.02	7,235.37	1.32	.190

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Table 5

Experiment Two Session Two Reaction Time Linear Mixed Effect Summary Table (Continued)

Item	Estimate	*SD*	*df*	*t*	*p*
Congruency Incongruent: Entrainment 30Hz	0.02	0.02	7,237.18	1.06	.290
Target Timing Further Delay: Entrainment 4.6Hz	-0.01	0.02	7,234.70	-0.49	.630
Target Timing In Sync: Entrainment 4.6Hz	0.00	0.02	7,234.77	0.06	.950
Target Timing Premature: Entrainment 4.6Hz	0.01	0.02	7,235.06	0.71	.480
Target Timing Further Delay: Entrainment 10Hz	0.01	0.02	7,234.80	0.32	.750
Target Timing In Sync: Entrainment 10Hz	-0.01	0.02	7,234.41	-0.80	.430
Target Timing Premature: Entrainment 10Hz	0.03	0.02	7,234.75	1.62	.100
Target Timing Further Delay: Entrainment 30Hz	-0.01	0.02	7,235.00	-0.69	.490
Target Timing In Sync: Entrainment 30Hz	-0.03	0.02	7,234.83	-1.47	.140
Target Timing Premature: Entrainment 30Hz	0.04	0.02	7,235.86	1.97	.050

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Table 5

Experiment Two Session Two Reaction Time Linear Mixed Effect Summary Table (Continued)

Item	Estimate	*SD*	*df*	*t*	*p*
Congruency Incongruent: Target Timing Further Delay: Entrainment 10Hz	0.01	0.02	7,234.75	0.33	.740
Congruency Incongruent: Target Timing In Sync: Entrainment 4.6Hz	0.01	0.02	7,234.85	0.49	.620
Congruency Incongruent: Target Timing Premature: Entrainment 4.6Hz	-0.01	0.02	7,234.86	-0.30	.770
Congruency Incongruent: Target Timing Further Delay: Entrainment 10Hz	-0.02	0.02	7,234.68	-0.94	.350
Congruency Incongruent: Target Timing In Sync: entFreq10	0.02	0.02	7,234.95	0.70	.480
Congruency Incongruent: Target Timing Premature: Entrainment 10Hz	-0.04	0.02	7,234.92	-1.76	.080
Congruency Incongruent: Target Timing Further Delay: Entrainment 30Hz	0.01	0.03	7,235.61	0.33	.740
Congruency Incongruent: Target Timing In Sync: Entrainment 30Hz	0.04	0.03	7,235.76	1.42	.160

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Item	Estimate	*SD*	*df*	*t*	*p*
Congruency Incongruent: Target Timing Further Delay: Entrainment 10Hz	0.01	0.02	7,234.75	0.33	.740
Congruency Incongruent: Target Timing Premature: Entrainment 30Hz	-0.03	0.03	7,235.91	-1.05	.290

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Table 6

Experiment Two Session Two End of Trial Microsaccade t-tests Result Table

group1	group2	*t*	*p*	*df*	adjusted *p*	conf_low	conf_high	estimate1	estimate2	_
.Delay	1.Further Delay	-0.88	.379	136.70	1.00	-0.00	0.00	0.01	0.01	ns
1.Delay	1.In Sync	-0.58	.566	126.19	1.00	-0.00	0.00	0.01	0.01	ns
1.Delay	1.Premature	-1.83	.070	110.01	1.00	-0.01	0.00	0.01	0.01	ns
1.Further Delay	1.In Sync	0.40	.690	136.66	1.00	-0.00	0.00	0.01	0.01	ns
1.Further Delay	1.Premature	-0.94	.348	124.55	1.00	-0.00	0.00	0.01	0.01	ns
1.In Sync	1.Premature	-1.42	.159	103.98	1.00	-0.00	0.00	0.01	0.01	ns
10.Delay	10.Further Delay	-2.05	.046*	44.85	1.00	-0.01	-0.00	0.01	0.01	ns
10.Delay	10.In Sync	-1.27	.210	62.92	1.00	-0.00	0.00	0.01	0.01	ns
10.Delay	10.Premature	-1.05	.300	53.33	1.00	-0.00	0.00	0.01	0.01	ns

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Table 6

Experiment Two Session Two End of Trial Microsaccade t-tests Result Table (Continued)

group1	group2	*t*	*p*	*df*	adjusted p	conf_low	conf_high	estimate1	estimate2	_
10.Further Delay	10.In Sync	1.11	.272	44.03	1.00	-0.00	0.01	0.01	0.01	ns
10.Further Delay	10.Premature	1.00	.320	51.89	1.00	-0.00	0.01	0.01	0.01	ns
10.In Sync	10.Premature	0.01	.992	51.94	1.00	-0.00	0.00	0.01	0.01	ns
30.Delay	30.Further Delay	-0.22	.826	51.81	1.00	-0.00	0.00	0.01	0.01	ns
30.Delay	30.In Sync	-0.18	.857	46.37	1.00	-0.00	0.00	0.01	0.01	ns
30.Delay	30.Premature	-0.95	.348	52.96	1.00	-0.00	0.00	0.01	0.01	ns
30.Further Delay	30.In Sync	0.04	.965	48.97	1.00	-0.00	0.00	0.01	0.01	ns
30.Further Delay	30.Premature	-0.59	.560	47.97	1.00	-0.00	0.00	0.01	0.01	ns
30.In Sync	30.Premature	-0.67	.508	42.59	1.00	-0.00	0.00	0.01	0.01	ns

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Table 6

Experiment Two Session Two End of Trial Microsaccade t-tests Result Table (Continued)

group1 (entrained frequency. Target Timing)	group2 (entrained frequency .Target Timing)	*t*	*p*	*df*	adjusted p	conf_low	conf_high	estimate1	estimate2	_
4.Delay	4.Further Delay	-2.57	.013*	45.64	0.32	-0.01	-0.00	0.01	0.01	ns
4.Delay	4.In Sync	-0.43	.668	62.81	1.00	-0.00	0.00	0.01	0.01	ns
4.Delay	4.Premature	-1.84	.073	48.51	1.00	-0.01	0.00	0.01	0.01	ns
4.Further Delay	4.In Sync	2.15	.037*	47.01	0.88	0.00	0.01	0.01	0.01	ns
4.Further Delay	4.Premature	0.75	.456	47.66	1.00	-0.00	0.01	0.01	0.01	ns
4.In Sync	4.Premature	-1.41	.165	49.41	1.00	-0.01	0.00	0.01	0.01	ns

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Table 7

Experiment Two Session Two, During Trial Microsaccade Rate Continuity

Item	Continuity start	Continuity end	Continuity duration
1	8,095.00	8,117.00	23.00
2	8,119.00	8,143.00	25.00
3	8,146.00	8,170.00	25.00
4	8,177.00	8,182.00	6.00
5	8,361.00	8,361.00	1.00
6	8,406.00	8,419.00	14.00
7	9,221.00	9,221.00	1.00
8	9,233.00	9,307.00	75.00
9	9,309.00	9,319.00	11.00
10	9,323.00	9,331.00	9.00
11	10,129.00	10,135.00	7.00
12	10,137.00	10,137.00	1.00
13	10,141.00	10,152.00	12.00
14	10,154.00	10,154.00	1.00
15	10,160.00	10,163.00	4.00
16	10,383.00	10,388.00	6.00
17	10,467.00	10,469.00	3.00
18	10,471.00	10,473.00	3.00
19	10,479.00	10,480.00	2.00

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Table 7

Experiment Two Session Two, During Trial Microsaccade Rate Continuity (Continued)

Item	Continuity start	Continuity end	Continuity duration
20	10,482.00	10,509.00	28.00
21	10,807.00	10,808.00	2.00
22	10,830.00	10,837.00	8.00
23	10,842.00	10,844.00	3.00
24	10,846.00	10,846.00	1.00
25	10,851.00	10,852.00	2.00
26	10,858.00	10,869.00	12.00

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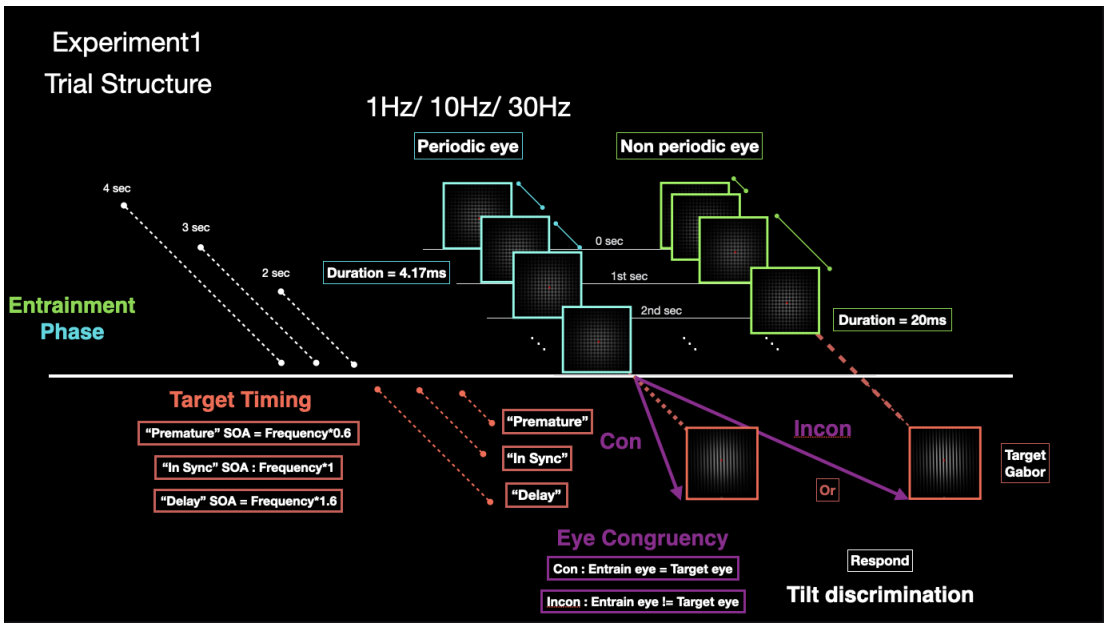
Figures

Figure 1

Experiment One Trial Structure



Note. Three frequencies were tested in Experiment One. Periodic flicker (light blue) was presented on one eye, non-periodic flicker (light green) was presented on the other eye. After entrainment, target (coral) was presented at different timing and location. Timing wise, the target could be presented at Premature, In Sync or Delay time point, the three SOA correspond to the three coral dashed lines. Location wise, the target could be presented at the same eye-of-entrainment (Congruent) or different from the eye-of-entrainment (Incongruent).

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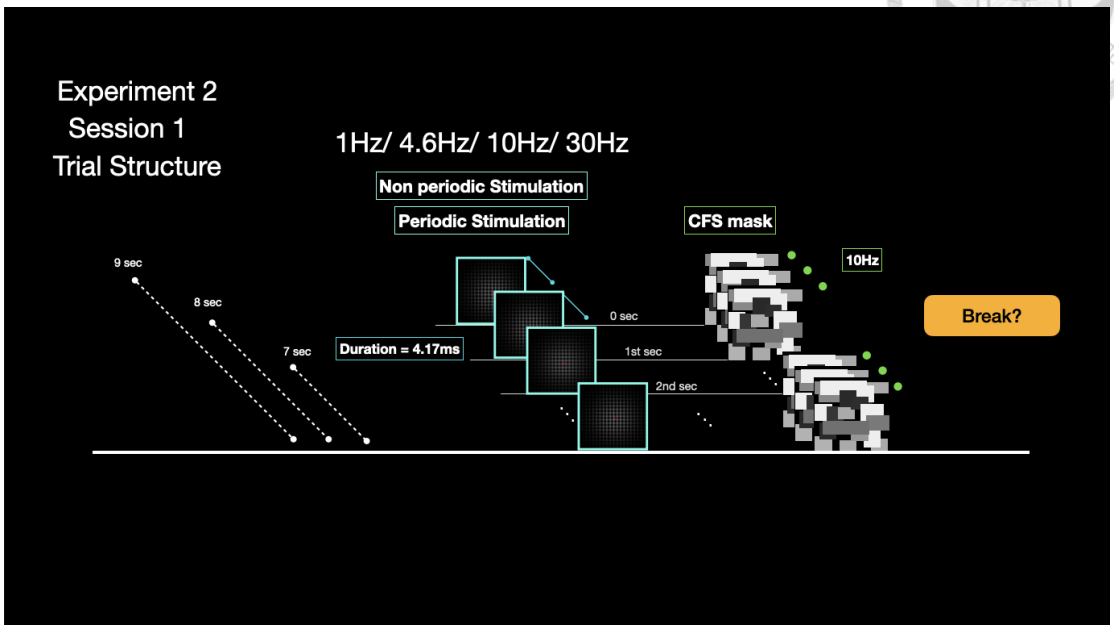
Figure 2

Experiment Two Session One Trial Structure



Note. Four frequencies were tested in Experiment Two. Periodic flicker (light blue) or non-periodic flicker (light blue) was presented on one eye, Mondrian mask was presented on the other eye. During entrainment, the observer had to press key to indicate awareness.

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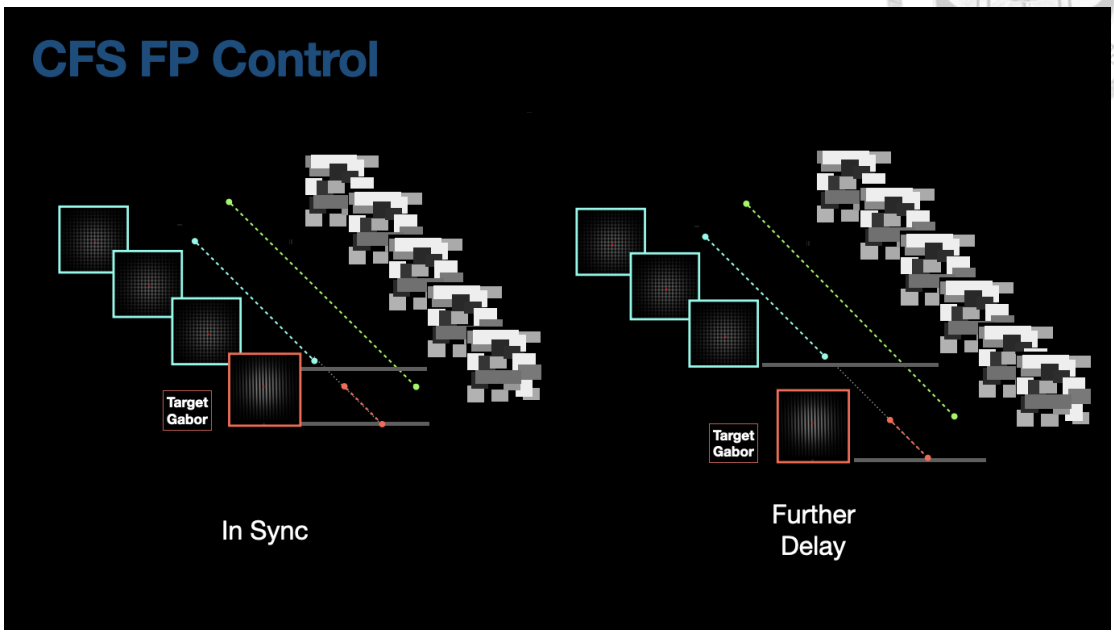
Figure 3

Experiment Two Session Two Foreperiod Control Illustration



Note. To control for the foreperiod effect within each frequency. The Mondrian masking (light green dashed line) extended past the *last entrainer* (the third light blue grating) to different degrees to ensure consistent time window between the offset of Mondrian masking to target(coral) onset. Put differently, regardless of the target timing, after applying the Mondrian extension, the temporal gaps (coral dashed line) were of the same length across target timing.

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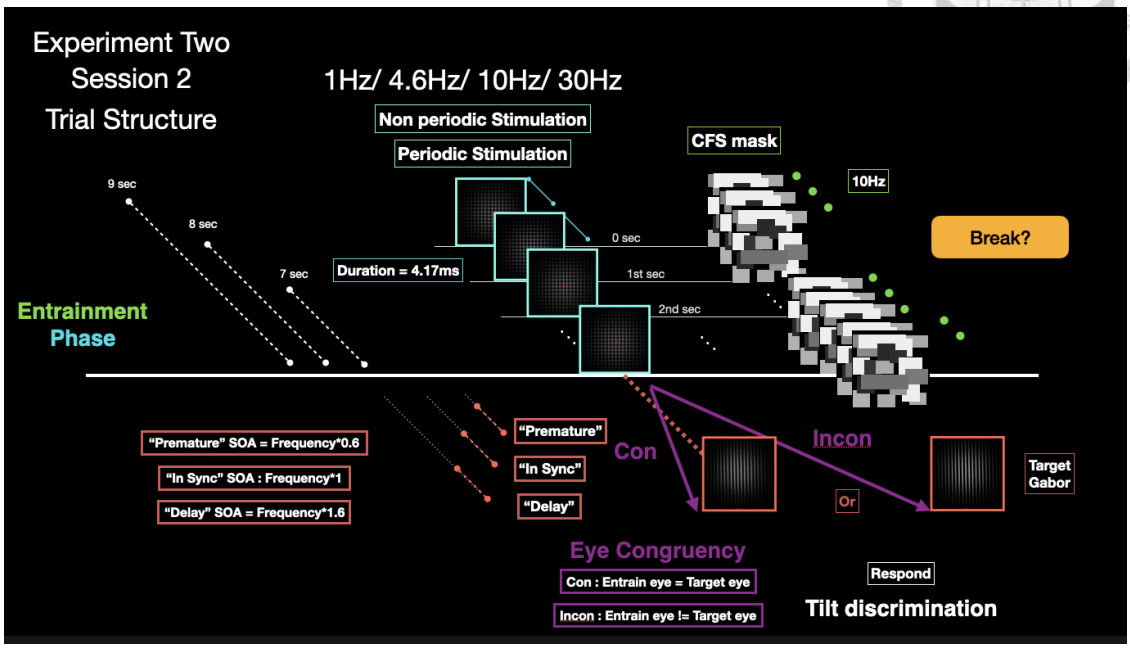
Figure 4

Experiment Two Session Two Trial Structure



Note. Four frequencies were tested in Experiment two. Similar to experiment one, Periodic flicker (light blue) was presented on one eye, Mondrian mask was presented on the other eye. During entrainment, the observers had to indicate awareness during entrainment with keypress. After entrainment, target (coral) was presented at different timing and location. Timing wise, the target could be presented at *Premature*, *In Sync*, *Delay*, or *Further Delay* time point, the four SOA correspond to the four coral dashed lines. Location wise, the target could be presented at the same eye-of-entrainment (Congruent) or different from the eye-of-entrainment (Incongruent).

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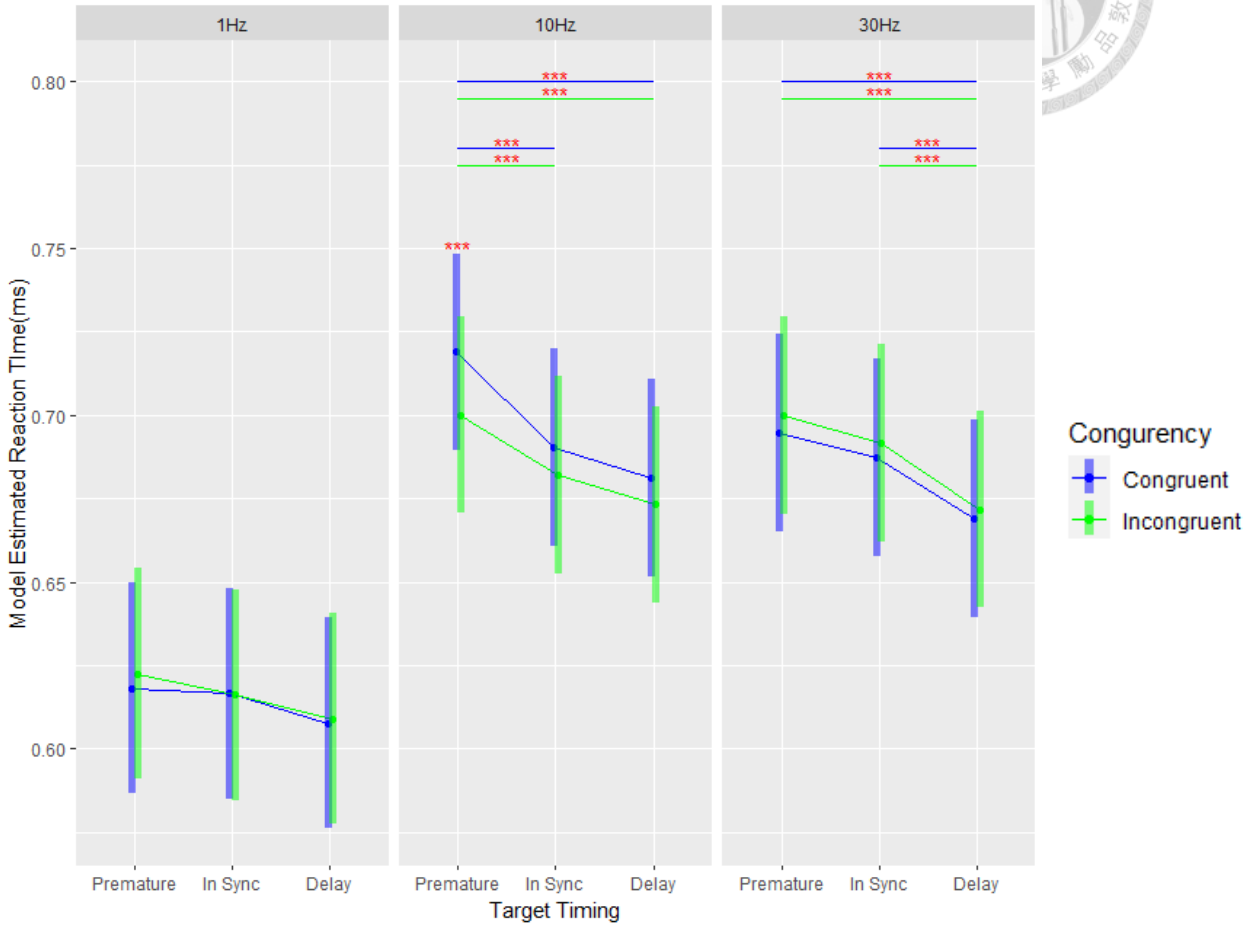
Figure 5

Experiment One Reaction Time Results



*Note***.** Data was fitted using linear mixed effect model with three fixed factors, *Target Timing*, *Entrained Frequency* and *Eye Congruency* with observer set as random factor.

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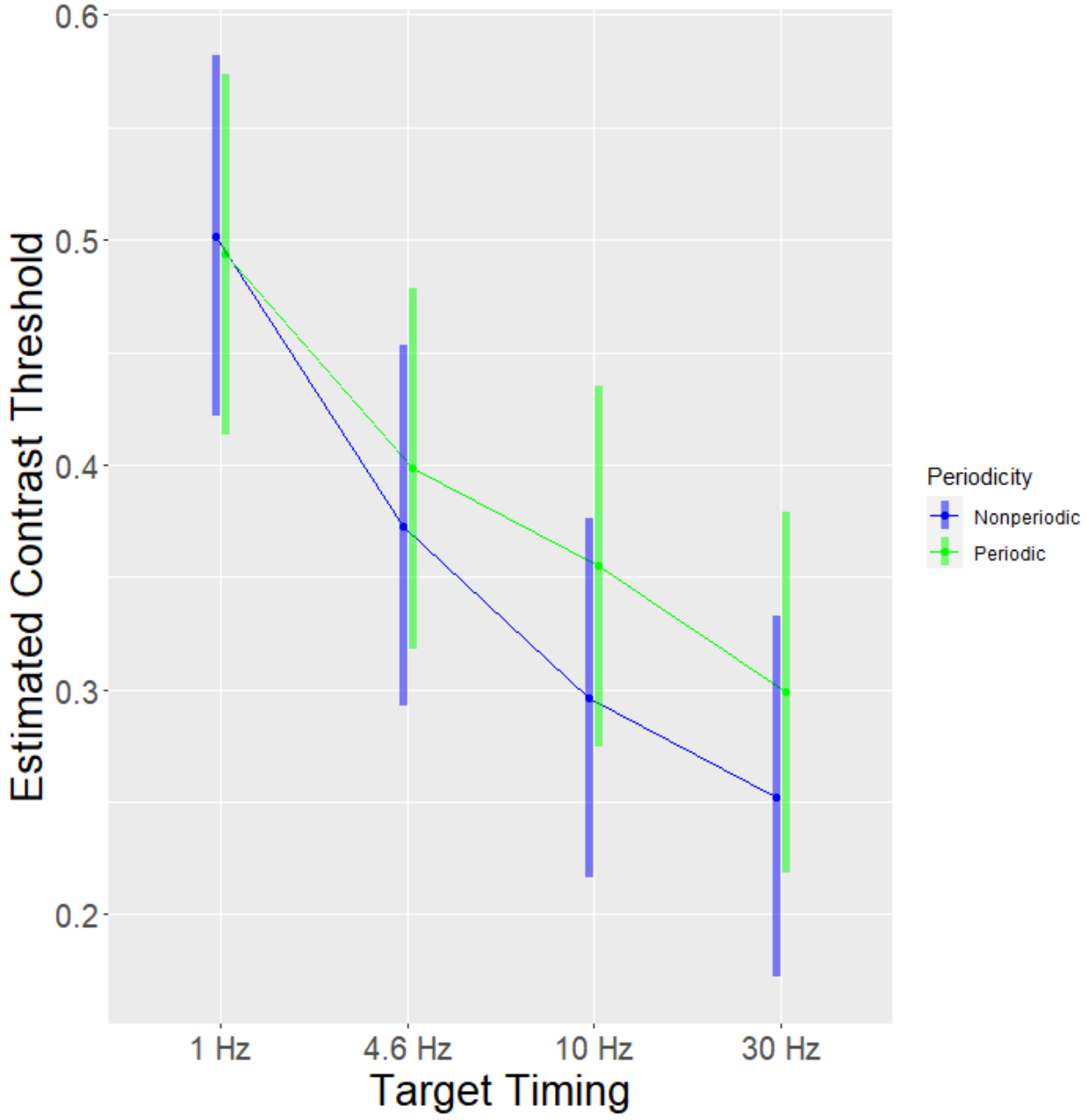
Figure 6

Experiment Two Session One Contrast Threshold Difference



Note. The estimates are LMM model estimated (Michelson) contrast threshold.

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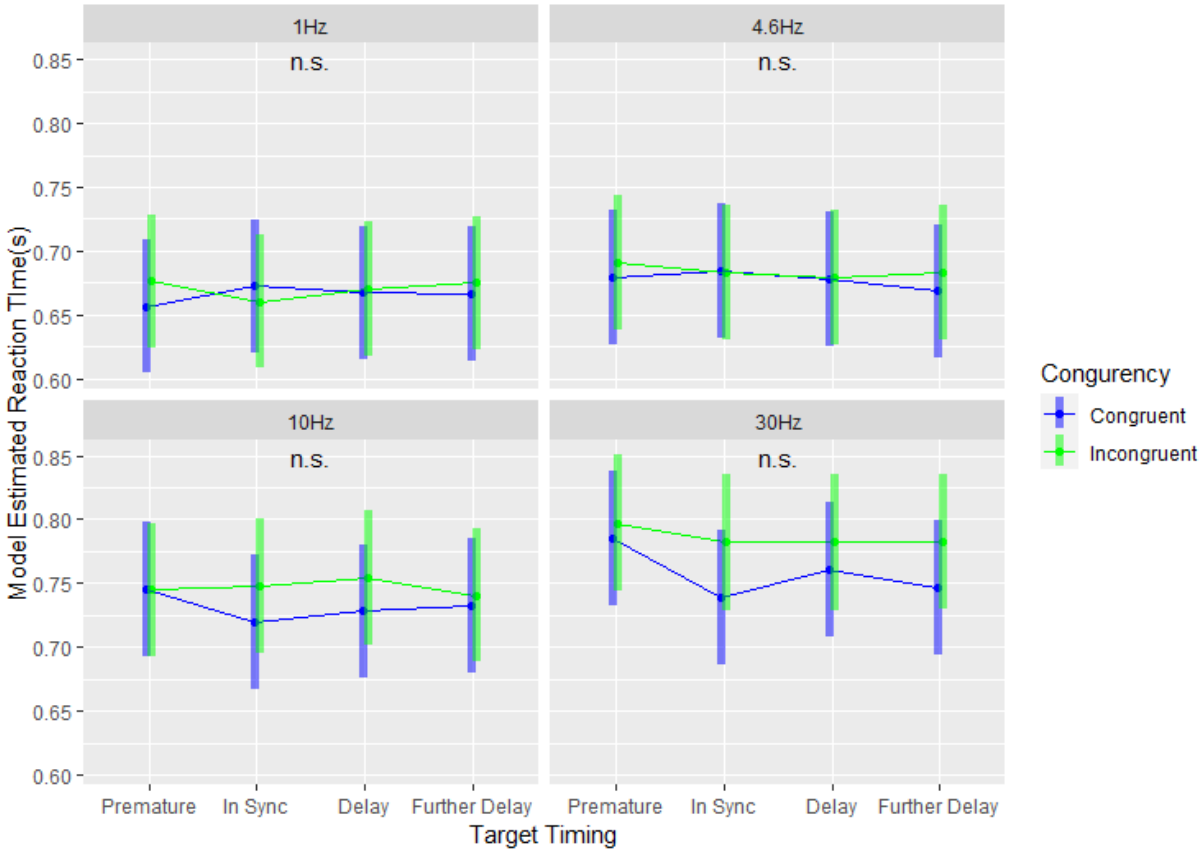
Figure 7

Experiment Two Session Two Reaction Time



Note. Data was fitted using linear mixed effect model with three fixed factors, *Target Timing*, *Entrained Frequency* and *Eye Congruency* with observer set as random factor.

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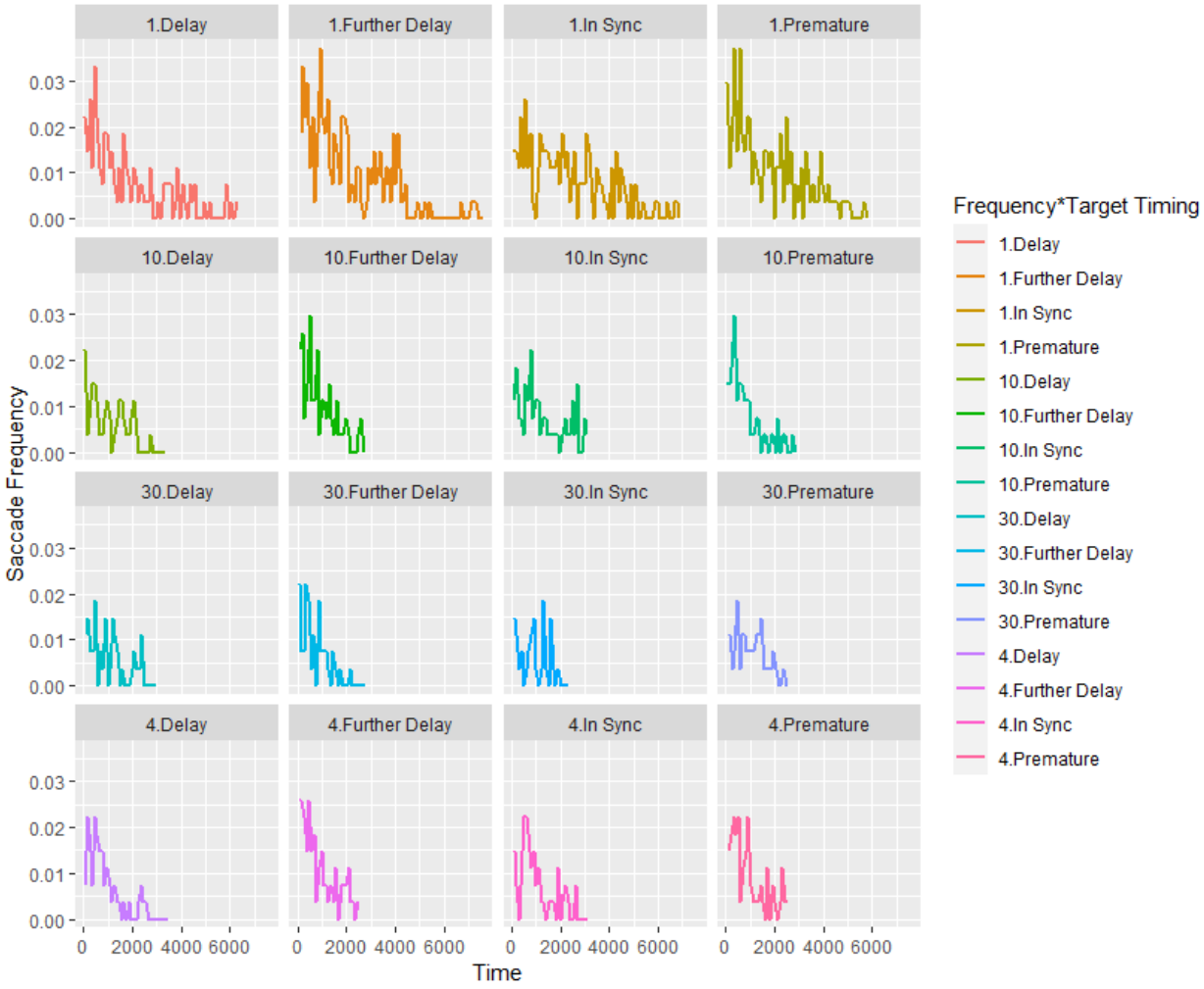
Figure 8

Experiment Two Session Two End of Entrainment Microsaccade Analysis



Note. The y-axis is the frequency of microsaccade. Zero point of x-axis is the offset of the Mondrian.

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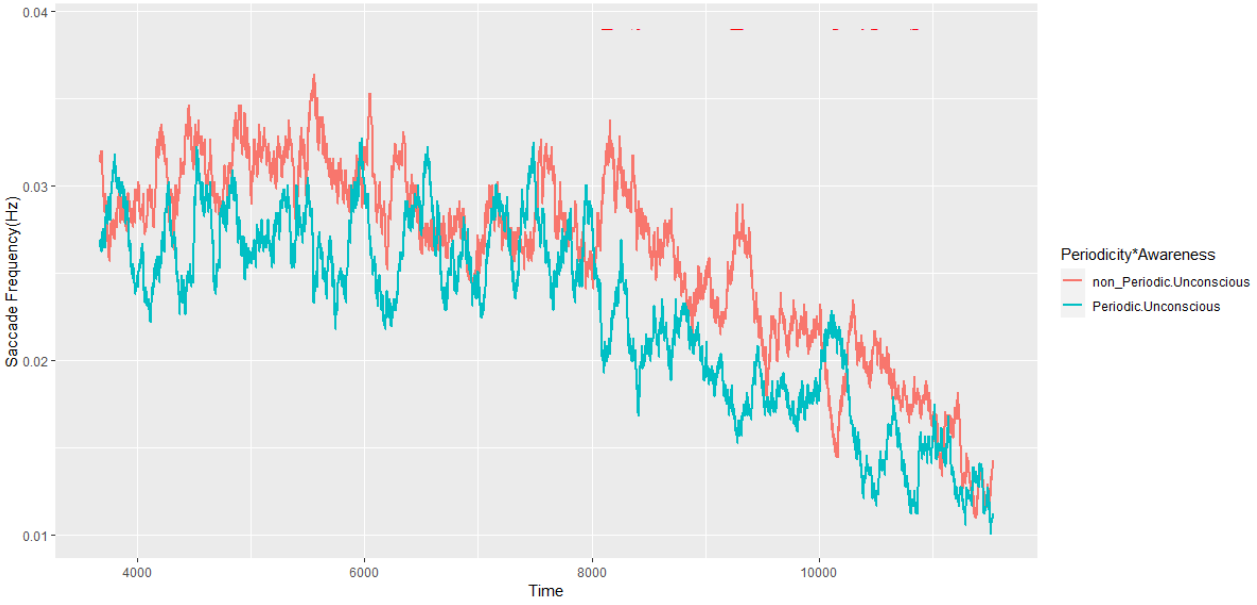
Figure 9

Experiment Two Session Two During Entrainment Microsaccade Analysis



Note. The y-axis is the frequency of microsaccade. Only the during entrainment dynamics were shown. The red markings denoted the statically significant comparisons.

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