

# Linear integration of multisensory signals in the pupil

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## Abstract

The pupil of the eye responds to various salient signals from different modalities, but there is no consensus on how these pupillary responses are integrated when multiple signals appear simultaneously. Both linear and nonlinear integration have been found previously. The current study aimed to reexamine the nature of pupillary integration, and specifically focused on the early, transient pupillary responses due to its close relationship with orienting. To separate the early pupillary responses out of the pupil time series, we adopted a pupil oscillation paradigm in which sensory stimuli were periodically presented. The simulation analysis confirmed that the amplitude of the pupil oscillation, induced by stimuli repeatedly presented at relatively high rates, can precisely reflect the early, transient pupillary responses without involving the late and sustained pupillary responses. The experimental results then showed that the amplitude of pupil oscillation induced by a series of simultaneous audiovisual stimuli equaled to a linear summation of the oscillatory amplitudes when unisensory stimuli were presented alone. Moreover, the tonic arousal levels, indicated by the baseline pupil size, cannot shift the summation from linear to nonlinear. These findings together support the additive nature of multisensory pupillary integration for the early, orienting-related pupillary responses. The additive nature of pupillary integration further implies that multiple pupillary responses may be independent of each other, irrespective of their potential cognitive and neural drivers.

## KEYWORDS

additive, multisensory integration, oscillation, pupil size, pupillary light reflex

## 1 | INTRODUCTION

Pupil size, controlled by the parasympathetic and the sympathetic pathways, is sensitive to light; it constricts in bright and relaxes in dark (Joshi & Gold, 2020; Mathôt, 2018; Steinhauer et al., 2022). Meanwhile, signals especially those with high salience are able to enlarge the pupil (Cherng et al., 2020; Wang & Munoz, 2015; Widmann et al., 2018; Zhao et al., 2019). In reality, dynamic sensing of the outside world inevitably encounters transient salient signals from multiple modalities, however, it has been poorly understood how these multisensory signals

collectively elicit an integrated pupillary response. In other words, whether the integrated pupillary response results from a linear summation of the isolated pupillary responses to unisensory signals or a nonlinear superadditive or subadditive summation.

Till now, there is no consensus on this issue. Two studies revealed that the integration of pupillary responses is linear additive (Van der Stoep et al., 2021; Wang et al., 2014). For instance, Van der Stoep et al. (2021) reported that the integrated pupillary responses to audiovisual stimuli in two different types of tasks did not significantly deviate from the linear summation of those pupillary responses

independently recorded. However, another study found the pupillary responses to audiovisual stimuli is nonlinear superadditive (Rigato et al., 2016). The purpose of the current study was to reexamine this issue and specifically focus on the integration of the early, transient pupillary responses evoked by multisensory signals.

Previous studies have found that salient stimuli can transiently orient or shift attention, leading to a rapid pupil dilation immediately after the stimulus abruptly occurs (Netser et al., 2010; Wang et al., 2017; Wang & Munoz, 2014) or when it appears among other repeated stimuli (Liao, Yoneya, et al., 2016; Murphy et al., 2011; Steiner & Barry, 2011; Widmann et al., 2018). This early orienting-related pupil dilation, most often arising and dissipating within 1 s, has almost the same latency as the pupillary light reflex (Mathôt, 2018; Wang et al., 2014; Wang & Munoz, 2015; Widmann et al., 2018). It is likely mediated by the parasympathetic inhibition (Steinhauer & Hakerem, 1992; Wang & Munoz, 2014; Widmann et al., 2018), and the superior colliculus-centered circuit (Strauch et al., 2022; Wang & Munoz, 2015). By exclusively focusing on the early pupillary responses closely associated with explicit cognitive functions, such as orienting, the current study has the potential to contribute toward resolving the ongoing debate regarding the nature of pupillary integration.

To this end, we recorded the fluctuations of pupil size when high-salient white noise bursts were presented alone or simultaneously with abruptly presented flashes. In Experiment 1, we examined the integration of pupillary responses to multisensory stimuli over time in a similar paradigm with previous studies (Rigato et al., 2016; Van der Stoep et al., 2021; Wang et al., 2014, 2017). In order to separate out the early pupillary responses that are routinely intermingled with the late and sustained pupillary responses, we applied a pupil oscillation paradigm (Clarke et al., 2003; Naber et al., 2013; Schwiedrzik & Sudmann, 2020; Yuan et al., 2021). First, we conducted a simulation analysis to demonstrate that the early pupillary responses can be separated and quantified by the amplitude of the pupil oscillation when the stimulus interval is remarkably shortened in the pupil oscillation paradigm. Second, we empirically recorded the pupil oscillation data at two purposely chosen 1.5 and 2 Hz stimulus onset rates in Experiment 2, and analyzed the amplitude of pupil oscillation induced by the noise bursts and the flashes. Based on the simulation, the pupil oscillatory amplitude at these two relatively fast onset rates can presumably reflect the early pupillary responses. By assessing and comparing whether the pupil oscillatory amplitude in response to noise bursts and flashes together are equal to their linear summation, we could delineate how early pupillary responses are integrated. Finally, since the time-locked

pupillary responses to external stimuli are modulated by the spontaneous tonic arousal levels (Gilzenrat et al., 2010; Murphy et al., 2011; van Kempen et al., 2019), we examined whether the pupillary integration varied from subadditive to superadditive as a function of the tonic arousal level indicated by the baseline pupil size (BPS).

## 2 | METHOD

### 2.1 | Participants

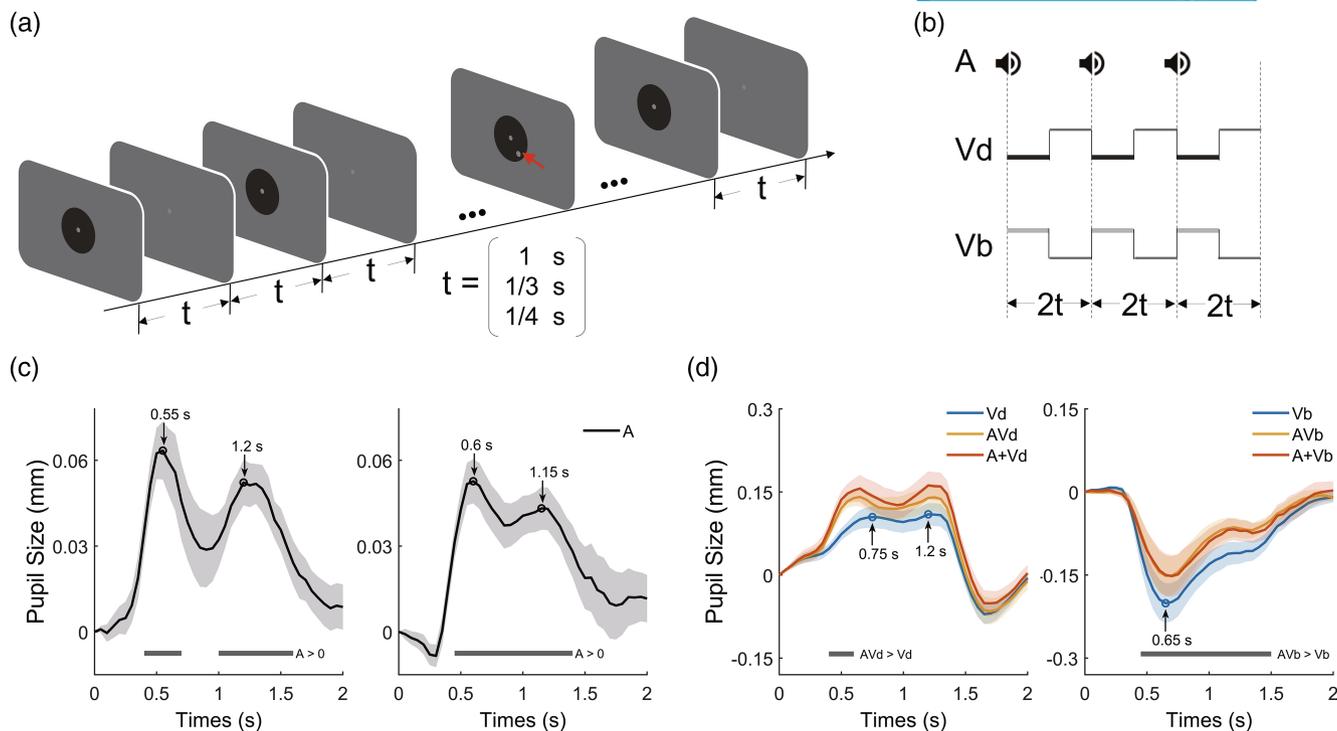
A total of 68 participants (33 female, mean age:  $23.96 \pm 3.19$  years) were recruited in the study, with 25 in Experiment 1 (11 females), 43 in Experiment 2 (22 females). All participants had normal or corrected-to-normal vision and normal hearing, and were naïve to the purpose of the experiments. They provided informed consent before experiments and were paid for their participation. The study was approved by the institutional review board of the Institute of Psychology, Chinese Academy Sciences and adhered to the tenets of the Declaration of Helsinki.

### 2.2 | Stimuli and apparatus

A 23-inch Alienware LCD screen was set at a viewing distance of about 60 cm (refresh rate: 60 Hz, resolution:  $1920 \times 1080$ ) in a dim, sound-attenuated room. We utilized an abrupt, short-lived white noise burst (0.15 s, sample rate: 44,100 Hz) as auditory stimuli. The noise bursts were played binaurally through headphones (Edifier H841P) and set at a constant  $\sim 50$  dB (A) throughout experiments. To elicit observable pupillary responses to visual stimuli, we displayed a bright ( $27.3 \text{ cd/m}^2$ ) or dark ( $7.6 \text{ cd/m}^2$ ) flash (radius:  $1.61^\circ$ ) against a gray background ( $17.1 \text{ cd/m}^2$ ) in the central field with a duration of 1, 1/3, or 1/4 s, respectively, in separate experiments (Figure 1a). All stimuli were generated by MATLAB (The MathWorks Inc.) together with Psychtoolbox (Brainard, 1997; Pelli, 1997).

### 2.3 | Task and procedures

In Experiment 1, the noise bursts, and the flashes were presented at a stimulus onset interval of 2 s (Figure 1a,b). In each trial, there are four repetitions of the audiovisual stimuli, during which small dots (diameter:  $0.25^\circ$ ) appeared for 0.05 s at random positions within the area occupied by the flash. In an orthogonal task, participants counted how many times they saw the dots to maintain



**FIGURE 1** General paradigm and Experiment 1 results. (a) An exemplar illustration in which the dark flash flickered against the grey background at different interval  $t$  in Experiments 1–2. The red arrow points out the small dot that participants ought to count in the orthogonal task. (b) In the A condition, the noise bursts were played against the background. In the V condition, either the dark or the bright flashes were viewed (Vd/Vb condition). (c) The black line refers to the pupil time series in response to the noise bursts for participants viewing the dark (left panel) or bright (right panel) flashes. (d) The pupil time series in response to flashes (V), to flashes synchronous with noise bursts (AV), and the summation of the A and V conditions are drawn as the blue, orange, and red lines for the two subsets of participants viewing the dark (left panel) and bright (right panel) flashes, respectively. The shaded areas in (c, d) represent SEM. The horizontal gray bars in (c, d) demonstrate the temporal clusters when the pupil responses in one condition significantly deviated from baseline or other conditions (FDR corrected). The black arrows indicate the peak latency at which the pupillary responses to auditory (c) or visual stimuli (d) reach their maximum or minimum of the average pupil time series across participants.

their attention in each trial. There were a total of 0–3 dots, randomly determined for each trial and never displayed at the same time. The dots, if presented on the flash, had an equal luminance with the background, and vice versa. At the end of each trial, participants input their answers using keyboards, and press the SPACE key to initiate the next trial after a short relaxation. There were four conditions (Figure 1b), the A condition in which only the noise bursts were presented, the V condition in which the flashes were silently presented, the AV condition in which they were simultaneously presented, and a catch-trial condition in which no stimulus was presented. There were 64 trials in total, divided into 4 blocks. In one block, each condition was repeated 4 times. Participants were separated into two subsets, with 14 exposed to the bright flash and 11 exposed to the dark flash.

Experiment 2 recorded the pupillary responses using a pupil oscillation paradigm, in which the stimulus onset interval in each trial was severely shortened (see the simulation analysis for the purpose of this design). That said, the procedure of Experiment 2 was identical to Experiment 1,

except that both the noise bursts and the flashes were periodically presented at an onset rate of 1.5 or 2 Hz during 8 s in each trial. Participants were separated into four subsets with ~10 in each. Ten and 12 participants watched the dark and bright flash at 1.5 Hz, respectively, while 11 and 10 participants watched the dark and bright flash at 2 Hz, respectively.

## 2.4 | Pupil recording and analysis

### 2.4.1 | Pupil recording and preprocessing

Participant's left eye was continuously monitored by a video-based iView X Hi-Speed system (SMI, Berlin, Germany) at 500 Hz. The eye tracker was calibrated by a 5-point standard procedure. The recorded pupil size was transformed and reported in the unit of mm. For each participant, the raw pupil diameter was visually inspected, and trials with obvious artifacts were excluded ( $1.36 \pm 2.29$ , and  $1.28 \pm 2.16$  trials excluded on average in

each experiment). For the remaining trials, blinks were automatically identified with the pre-blink shrinkage and post-blink recovery individually adjusted (within a range from  $-40$  to  $120$  ms), and linearly interpolated for complete removal of blink artifacts. The artifact-free pupil diameter was then downsampled to  $20$  Hz, averaged across trials for each condition, and baseline-normalized by subtracting the mean pupil size during the  $450$  ms pre-stimulus period. The average pupil time series in the A, V, and AV conditions were further corrected by point-to-point subtracting the average pupil time series in the catch-trial condition. This could remove the slow pupil changes, similar to applying a detrend. More importantly, to test whether the pupillary integration is linear additive, we needed to create a synthetic A + V condition as a standard, by linearly adding the corrected pupil time series in the A and V conditions together. Because the tonic pupil fluctuation contained in the unisensory pupil time series due to expectancy, arousal, or other confounding factors may be added to their sum twice, we have to approximately measure this component by the catch trial and remove it. This is the common practice when comparing multisensory responses with the sum of unisensory responses (Calvert & Thesen, 2004; Senkowski et al., 2011; Werner & Noppeney, 2010).

## 2.4.2 | Experiment 1

In Experiment 1, for each participant, we segmented the corrected pupil time series in each condition into four 2-s epochs to obtain the pupillary response to a single noise burst or a flash. These epochs were aligned to its first sample point and averaged for each condition. As for statistics, we first compared the corrected pupil time series in the A condition with zero using one-sample  $t$ -test to reveal the temporal clusters when the pupil was significantly dilated from the tonic pupil fluctuation in the catch-trial condition (Figure 1c). Next, we conducted consecutive paired-sample  $t$ -tests to compare the corrected pupil time series between the V and AV conditions, and between the AV and A + V conditions separately, to evaluate the integration of pupillary responses evoked by auditory and visual stimuli (Figure 1d). The inflation of false positives after multiple comparisons was controlled by FDR correction.

We also calculated their mean pupil size across time as a simpler proxy, and statistically compared it using a repeated measures ANOVA, with condition (V, AV, A + V) as the within-subject variable, and brightness (dark, bright) as the between-subject variable. Only the effects relevant to pupillary integration were reported and all the post hoc  $t$ -test statistics were Bonferroni corrected. The Bayesian

factor ( $BF_{10}$ ), which can provide quantitative evidence for alternative hypothesis ( $H_1$ ) or null hypothesis ( $H_0$ ), were calculated as well. All the statistics were performed in MATLAB and Jamovi (Şahin & Aybek, 2019).

## 2.4.3 | Simulation

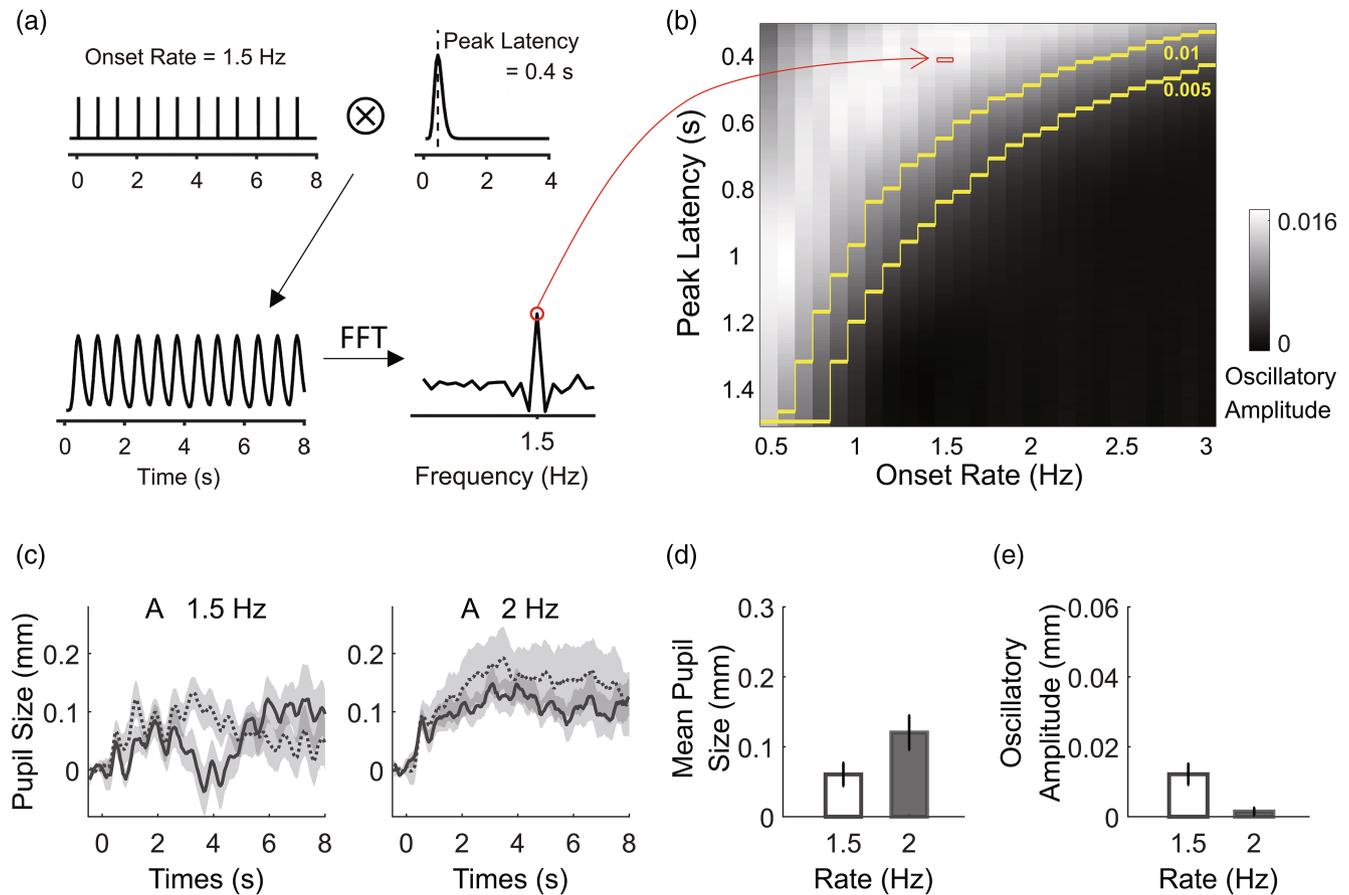
If a stimulus displayed alone evokes a pupillary response, we would usually observe a pupil oscillation when the stimulus is repeatedly presented (Clarke et al., 2003; Naber et al., 2013; Schwiedrzik & Sudmann, 2020; Yuan et al., 2021). The simulation was to illustrate that when the stimulus repetition rate (or the stimulus onset rate) is remarkably increased, the observed pupil oscillation is primarily contributed by the early, transient pupillary responses. Hence, it can serve as a valuable tool for determining the optimal stimulus onset rate in the pupil oscillation paradigm, allowing for the effective isolation of early pupillary responses from the overall pupil series.

In the current study, the simulated time series were generated as a linear combination of a series of discrete stimulations each convolved with a weighted pupil impulse response function (IRF):

$$h(t) = t^w \times e^{-wt/t_{\max}},$$

where  $t$  represents the times in ms, ( $w = 10.1$ ) controls the shape of the canonical IRF,  $t_{\max}$  represents the peak latency of the dilatory response (Hoeks & Levelt, 1993). The weight of the IRF was determined by the empirical data of Experiment 1, the A condition.

We sampled both the peak latency of the IRF and the stimulus onset rate out of a finite range, and simulated the pupil time series using the convolution method for each of their combination (Figure 2a). Random Gaussian noise was added to these simulated pupil time series to match the coefficient of variance obtained from Experiment 1, the A condition. A fast Fourier Transform (FFT, see Section 2.4.4 for details) was conducted to extract the oscillatory amplitude of the simulated pupil time series at the stimulus onset rate. We ran the above procedure 1000 times and generated the distribution of oscillatory amplitudes for each combination. For a given onset rate, we calculated the posterior probabilities that the oscillatory amplitudes larger than a given value stem from a pupillary response with a peak latency in the range of  $0.3$ – $1.5$  s [e.g.,  $P_{(\text{peak latency}=0.6|\text{oscillatory amplitude} > 0.005, \text{onset rate}=1.5 \text{ Hz})}$ ], and plotted the boundary in yellow (Figure 2b). The cumulative probability that these oscillatory amplitudes larger than the given value originate from the pupillary responses with peak latencies below this boundary is less than 1%. Based on the simulation, we chose two



**FIGURE 2** Results of the simulation, and the auditory condition in Experiment 2. (a) Schematic protocols of the simulation. A pupil time series was generated by a linear combination of discrete stimulations (here at 1.5 Hz) each convolved with a pupil impulse response function (here with a peak latency of 0.4 s). The oscillatory amplitude of this simulated pupil time series was extracted by FFT, and filled into its corresponding grid in (b). Given that the oscillatory amplitude is larger than 0.005 or 0.01, the posterior probability of pupillary responses with a peak latency below the yellow lines accumulates to 1%. (c) The pupil time series induced by auditory stimuli at 1.5 Hz (left panel) and 2 Hz (right panel) for participants viewing the dark (solid lines) or bright (dot lines) flashes. The mean pupil size (d) and the oscillatory amplitude (e) of the pupil time series. The shaded areas in (c) and error bars in (d, e) represent SEM.

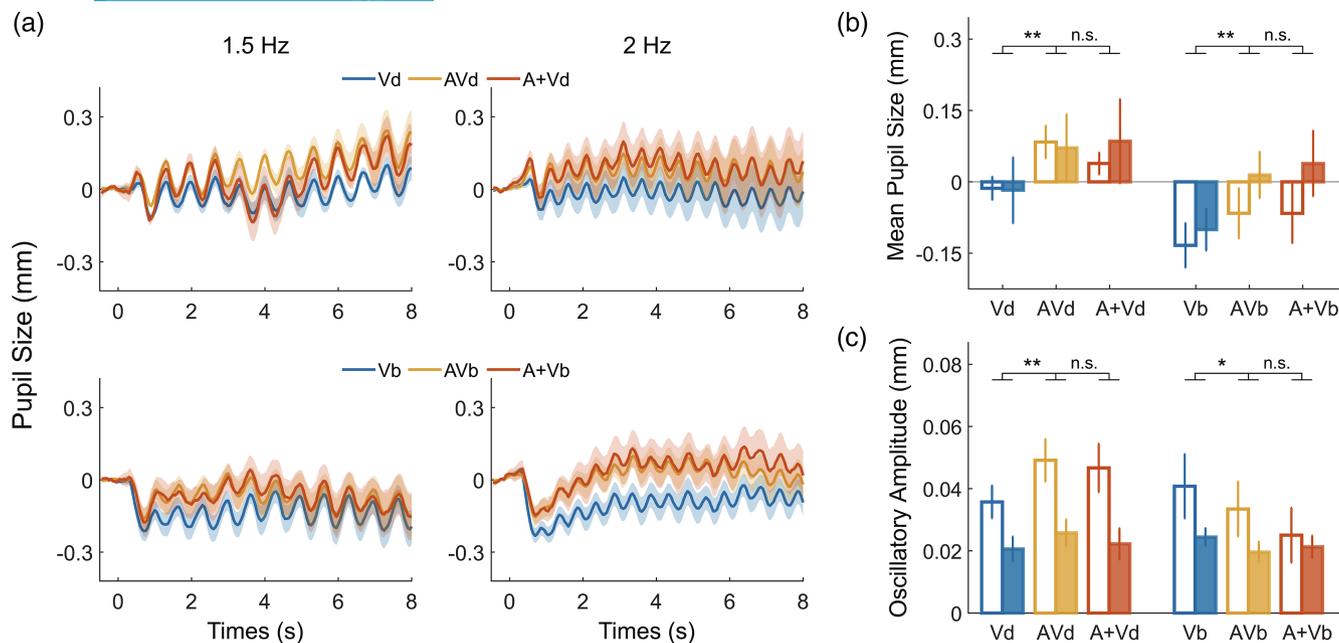
representative stimulus onset rates for Experiment 2 (1.5 and 2 Hz) that could isolate out the early orienting-related pupillary responses, and evaluated how these responses are integrated.

#### 2.4.4 | Experiment 2

In Experiment 2, where the pupil continuously oscillated at the stimulus onset rate in each trial (Figures 2c and 3a), we first averaged the pupil size across time for each condition and statistically compared them using the repeated measures ANOVA as did in Experiment 1. The condition (V, AV, A + V) was defined as the within-subject variable, while the brightness (dark, bright) and the rates (1.5, 2 Hz) as the between-subject variables. Similarly, we reported only the effects relevant to pupillary integration, corrected all the post-hoc *t* statistics by Bonferroni method, and calculated the  $BF_{10}$ .

Following other studies (Naber et al., 2013; Yuan et al., 2021), a FFT was conducted to extract the oscillatory amplitude at the stimulus onset rate. We submitted the corrected pupil time series for each condition into FFT, wherein the first second was discarded to exclude the response to stimulus onset. The oscillatory amplitude was calculated as the modulus of the FFT complex coefficients for each condition, and normalized by subtracting the average amplitude across its nearby two frequency points ( $\pm 0.1$  Hz). Here, we also conducted a 3 (condition)  $\times$  2 (brightness)  $\times$  2 (rate) repeated measures ANOVA on the oscillatory amplitude, reported effects of most interest, corrected all the post hoc *t* statistics by Bonferroni method, and calculated the  $BF_{10}$ .

We further investigated whether the nature of pupillary integration is affected by the tonic arousal state (indexed by the BPS). According to previous studies (Gilzenrat et al., 2010; Knapen et al., 2016; van Kempen et al., 2019; Wang & Munoz, 2014), we sorted the pupil time series



**FIGURE 3** Results of Experiment 2. (a) The mean corrected pupil time series when the flashes were dark (top) or bright (bottom) repeated at 1.5 (left) /2 Hz (right) in Experiment 2. Shaded areas, SEM. The mean pupil size (b) and oscillatory amplitude (c) for the dark (left) and bright flash (right) at 1.5 (hollow bars) or 2 Hz (solid bars). The SEM were plotted on each bar. \* $p < .05$ ; \*\* $p < .01$ ; n.s., not significant.

in terms of their BPS into three bins for each condition: five trials for the small baseline, five trials for the large baseline, and the other trials for the medium baseline. The BPS, the mean pupil size and the oscillatory amplitude were averaged across trials per bin for each condition (with outliers excluded using the *isoutlier* function, “grubbs” algorithm in MATLAB).

These pupil bin data were then entered into a linear mixed model (LMM) to statistically evaluate their relationship. The model tested for each condition whether the mean pupil size and the oscillatory amplitude (both termed pupillary response, PR in the equation below for convenience) can be predicted by the BPS with *brightness* (dark or bright flash), *speed* (1.5 or 2 Hz) simultaneously included. The mean pupil size and oscillatory amplitude in each condition were separately regressed as a linear combination of the *brightness*, *speed* and BPS:

$$PR \sim \beta_0 + \beta_l \times \text{brightness} + \beta_s \times \text{speed} + \beta_b \times \text{BPS},$$

with  $\beta$  as the coefficients, and participant as a random intercept.

To assess whether the BPS affected the pupillary integration effect (the pupillary response to AV minus the sum of those to A and V,  $\Delta PR$  in the equation), the pupil bin data were sent into another LMM:

$$\Delta PR \sim \beta_0 + \beta_l \times \text{brightness} + \beta_s \times \text{speed} + \beta_b \times \text{BPS},$$

with  $\beta$  as the coefficients, and participant as a random effect as well. Specifically,  $\Delta PR$  per bin was calculated by

subtracting the mean pupil size or the oscillatory amplitude of each bin in the A+V condition from that of the corresponding bin in the AV condition (e.g., both from the bins with large BPS), and the BPS per bin were averaged across the same bins in these two conditions. It is worth noting that since the noise bursts had opposite effects on the pupil oscillation induced by flashes with different luminance (see Results, Figure 3c), we reversed the sign of the  $\Delta PR$  in terms of oscillatory amplitude for the bright flashes to align with that for the dark flashes.

### 3 | RESULTS

We investigated multisensory integration in the pupil of the eye through two experiments. Participants were randomly divided into subsets ( $n = \sim 10$ ), watching either dark or bright flashes presented against a grey background at different rates (Figure 1a,b, the Vd/Vb condition). A series of abrupt, white noise bursts were played at the same rate with the flash (the A condition). They were synchronized in time when displayed together (the AV condition). During pupil recording, we required participants to perform an orthogonal task so as to monitor their sustained attention. In each trial, they counted the number of small dots briefly displayed on the screen (Figure 1a). Their mean accuracies of each condition in all experiments were higher than 96% (SDs <6%), which indicated they had devoted sufficient attention to the stimuli.

### 3.1 | Experiment 1

Experiment 1 set the stimulus onset interval to 2s. First, it is demonstrated that the noise bursts evoked a significant pupil dilation, meanwhile, the dark and bright flashes evoked a typical pupillary dark and light reflex individually (Figure 1c,d). Furthermore, the noise bursts significantly enhanced the pupil dilation to dark flashes and inhibited the pupil constriction to bright flashes (Figure 1d). This indicates that the pupillary responses to visual stimuli are additionally enlarged by auditory stimuli. After linear summation of the pupil time series in the A and V condition to create a synthetic A + V condition (Figure 1d, the red lines), we directly compared the pupil fluctuation in the AV condition with the A + V condition, but found no significant differences (the orange and red lines in Figure 1d). Consistently, the mean pupil size in the V condition was also linearly enlarged by the noise bursts, and the mean pupil size in the AV condition was not significantly deviated from that in the A + V condition (the main effect of condition:  $F(2, 46) = 16.18, p < .001, \eta_p^2 = 0.41$ ; AV vs. V:  $t(24) = 4.03, p = .001, BF_{10} = 65.90$ ; AV vs. A + V:  $t(24) = -0.78, p > .9, BF_{10} = 0.28$ ). The  $BF_{10}$  was 0.28 for the difference between the AV and A + V conditions, with moderate evidence supporting a linear integration of pupillary responses relative to a nonlinear integration.

Additionally, concordant with other findings (Mathôt, 2018; Wang & Munoz, 2015; Widmann et al., 2018), the pupil dilation evoked by high-salient multisensory stimuli contained an early, transient component followed by a late, sustained one. As shown in Figure 1c,d, the average peak latency of the early pupillary responses was 0.55–0.75s, while the average peak latency of the late pupillary responses was 1.55–1.2s. Given that the early pupillary responses to multisensory signals are more closely linked to orienting, in the next we precisely explored how they are integrated. But it should be noted here that the early pupil dilation evoked by the abrupt appearance of a bright visual stimulus has been overshadowed by the pupil constriction to brightness increase, which is much larger in magnitude (comparison between the pupil size in Figure 1c,d right).

### 3.2 | Simulation

We aimed to leverage the pupil oscillation paradigm to isolate the early pupillary responses from the pupil time series in Experiment 2. But beforehand, we need to decide at which stimulus onset rate, the early pupillary responses can be exclusively measured by the amplitude of evoked pupil oscillation. To this end, we carried out a simulation, during which we calculated the oscillatory amplitudes from a group of pupil time series each generated

by convolving the pupil IRF at a certain peak latency with a design matrix of stimuli repeated at a certain rate (Figure 2a and Section 2).

The results of simulation are drawn in Figure 2b. It clearly demonstrates that the oscillatory amplitude will decrease when repeated stimuli are presented at relatively higher onset rate. We plotted two representative lines in yellow, the pupillary responses with peak latencies below which only have less than 1% chance of generating the oscillatory amplitudes larger than 0.01 and 0.005, respectively. The simulation revealed that at a relatively fast onset rate, the larger the oscillatory amplitude, the less likely it is induced by pupillary responses with a long peak latency. Given the results in Experiment 1 that the average peak latency of the early pupillary responses was 0.55–0.75s, we chose 1.5 and 2Hz as the representative stimulus onset rates for Experiment 2. The two relatively high rate ensured that the amplitude of pupil oscillation can quantify the early, transient pupillary responses with little confound by the late and sustained pupillary responses.

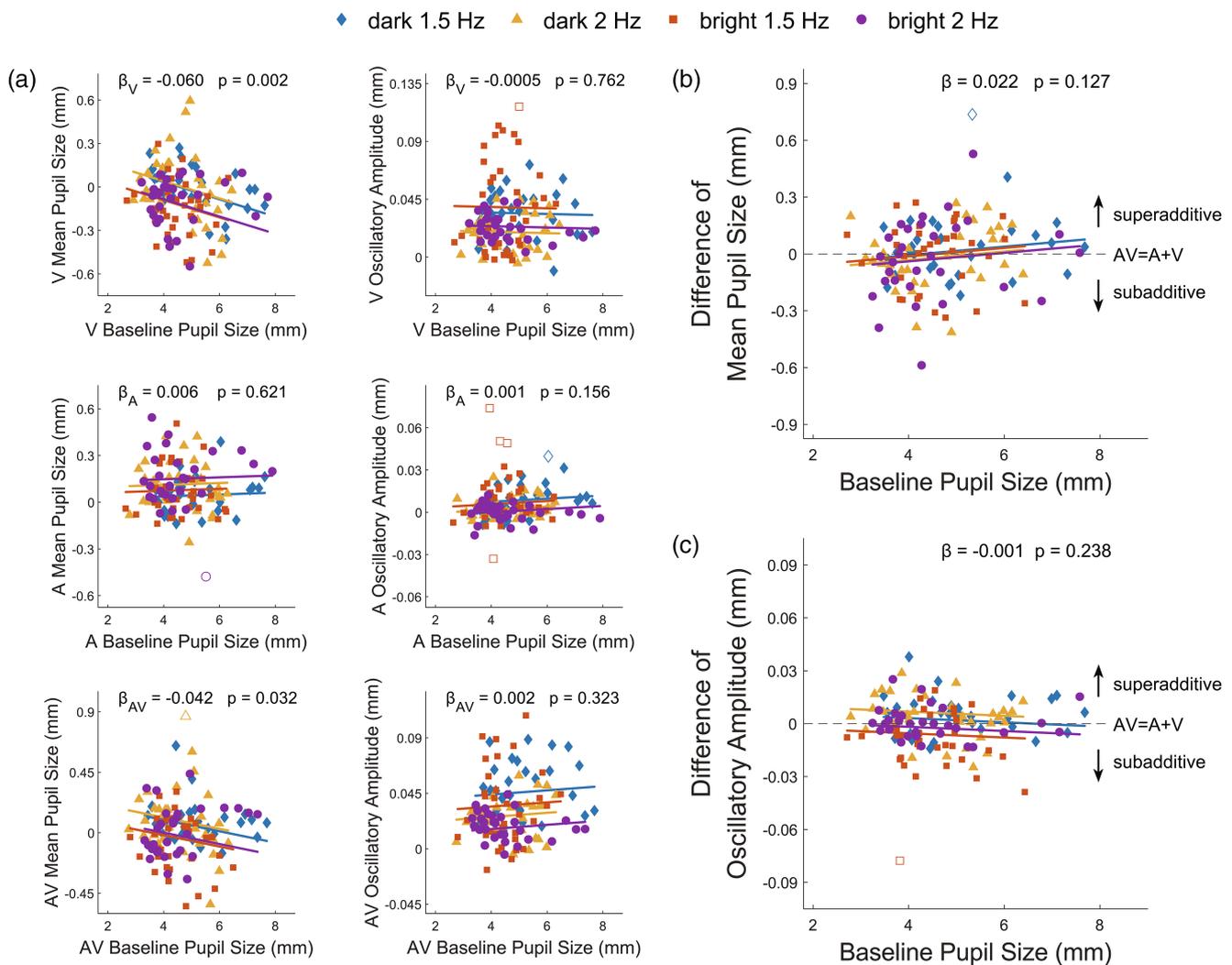
### 3.3 | Experiment 2

The simulation results have shown that in a pupil oscillation paradigm, the amplitude of pupil oscillation is able to precisely measure the early pupillary responses when stimuli onset rate is set to 1.5 or 2Hz. In Experiment 2, we presented the noise bursts and flashes at these two rates and tested whether the oscillatory amplitude in the AV condition significantly differed from that in the A + V condition, to reflect the linear or nonlinear integration of the early pupillary responses.

First of all, we found the noise bursts linearly enlarged the mean pupil size in the V condition, consistent with Experiment 1 (Figure 3a,b, the main effect of condition:  $F(2, 78) = 22.05, p < .001, \eta_p^2 = 0.36$ ; AV vs. V:  $t(42) = 5.73, p < .001, BF_{10} = 17,538.19$ ; AV vs. A + V:  $t(42) = 0.08, p > .9, BF_{10} = 0.17$ ). As in the simulation, a significant pupil oscillation was evoked by the series of noise bursts (Figure 2c–e,  $t(42) = 3.82, p < .001, BF_{10} = 62.80$ , especially at 1.5Hz,  $t(21) = 4.01, p < .001, BF_{10} = 53.55$ ; while for 2Hz, there was a same trend  $t(21) = 1.35, p = .19, BF_{10} = 0.50$ ). Similar with Experiment 1, the visually induced pupil oscillation was enhanced by the noise bursts for the dark flashes and inhibited for the bright flashes (Figure 3a,c, the interaction between condition and brightness:  $F(2, 78) = 17.42, p < .001, \eta_p^2 = 0.31$ ; AVd vs. Vd:  $t(20) = 4.60, p < .001, BF_{10} = 170.51$ ; AVb vs. Vb:  $t(21) = -3.26, p = .01, BF_{10} = 11.47$ ). Of our most interest, however, it did not show a nonlinear additivity either (A + Vd vs. AVd:  $t(20) = -1.68, p = .33, BF_{10} = 0.76$ ; A + Vb vs. AVb:  $t(21) = -1.85, p = .24, BF_{10} = 0.94$ ). Since the noise bursts

oppositely affected the pupillary light and dark reflex, we exchanged the oscillatory amplitude in the A + V and AV conditions for participants viewing the bright flashes and pooled them with the oscillatory amplitude for the dark flashes to increase statistic power. A paired-sample *t*-test showed the same trend (A + V vs. AV:  $t(42)=0.33$ ,  $p=.75$ ,  $BF_{10}=0.17$ ). The  $BF_{10}$  was 0.17 for the mean pupil size difference as well as the oscillatory amplitude difference between the AV and A + V conditions, which again provides moderate evidence for the linear integration of pupillary responses. These results demonstrated that even the early orienting-related pupillary responses were separately considered, the pupillary integration is approximately ruled by a linear additive algorithm.

To further investigate whether tonic arousal state interferes with the nature of pupillary integration, we sorted all the trials into three bins by the BPS for each condition and each participant of Experiment 2. The BPS, the pupillary responses to unisensory stimuli, and the pupillary integration effect (i.e., the pupillary response difference between the AV and A + V conditions) were then averaged across trials per bin. These pupil bin data were submitted to two LMM to assess their relationship. We found that the mean pupil size decreased linearly in the V and AV conditions but not in the A condition as the baseline pupil enlarged ( $\beta_V = -0.060$ ,  $p=.002$ ;  $\beta_{AV} = -0.042$ ,  $p=.032$ ;  $\beta_A = 0.006$ ,  $p=.621$ , see Figure 4a, left panels), whereas the oscillatory amplitude was not significantly affected by



**FIGURE 4** The relationship between baseline pupil size (BPS) and the pupillary integration. (a) The relationship between BPS and subsequent pupillary responses in each condition. Left: the impact of BPS on the mean pupil size in the V (top), A (middle), or AV (bottom) condition. Right: the impact of BPS on the oscillatory amplitude in the V (top), A (middle), or AV (bottom) condition. (b, c) The relationship between BPS and pupillary integration. The pupillary integration effect is calculated as the difference of the mean pupil size between AV and A + V conditions in (b), while calculated as the difference of the oscillatory amplitude between AV and A + V conditions in (c). Superadditive:  $AV > A + V$ , subadditive:  $AV < A + V$ . The data from each individual were shown by the solid shapes with outliers by hollows. Each line represents the prediction of the fitted linear mixed model.

the BPS ( $ps > .15$ , see [Figure 4a](#), right panels). Critically, we quantified the transition of the pupillary integration from subadditive to superadditive by the pupillary integration effect, and found such effect was not modulated by the BPS, neither for the mean pupil size ( $\beta = 0.022$ ,  $p = .127$ , [Figure 4b](#)), nor for the oscillatory amplitude ( $\beta = -0.001$ ,  $p = .238$ , [Figure 4c](#)). By and large, these analyses together demonstrated the levels of tonic arousal state may only modulate the late and sustained pupillary responses but not the early orienting-related pupillary responses. Nonetheless, the pupillary integration mechanism is almost insensitive to the tonic arousal state.

## 4 | DISCUSSION

The current study illustrated how multisensory signals integratedly modulate the pupil size, especially the integration of early orienting-related pupillary responses. The results of two experiments clearly and convergently demonstrated that a salient noise burst enhanced the pupil dilation to dark flashes but inhibited the pupil restriction to bright flashes. Despite differentially manifested, both the impacts can be seen as a sound-induced pupil dilation linearly overlapped onto the pupillary responses to flashes. No robust evidence supported that these pupillary responses are nonlinearly integrated, consistent with two previous studies (Van der Stoep et al., 2021; Wang et al., 2014) but different from another one (Rigato et al., 2016).

According to the inverse effectiveness principle revealed by a body of behavioral and neural studies, the weaker the salience or the intensity of the unisensory stimuli, the more probable the superadditive, nonlinear integration is observed (Noesselt et al., 2010; Senkowski et al., 2011; Stein et al., 2020; Stevenson & James, 2009; Werner & Noppeney, 2010). As stimuli with lower intensity evoke smaller pupillary responses, it is possible when sound intensity and flash contrast are purposely reduced, a nonlinear integration of pupillary responses (e.g., superadditive) would be observed. Since Rigato et al. (2016) did not report the actual stimulus intensity in their experiment, it cannot be directly compared with others that reported linear integration (Van der Stoep et al., 2021 and the present study). The comparison between our results and Van der Stoep et al. (2021) showed that the pupillary integration remains additive even though the noise intensity and the flash contrast in our study were lower than theirs. It may be argued that these findings are simply due to a ceiling effect that the integration of two dilated pupillary responses is physiologically not allowed to exceed the upper extreme of pupil size, which consequently reduces the likelihood to observe a superadditive summation. But this possibility can be falsified because the integration of

two counterbalanced pupillary responses, such as, a light-induced pupil constriction and a sound-induced pupil dilation also manifests as linear additive both in Van der Stoep et al. (2021) and our study.

Given that white noises are naturally more salient and noticeable than pure tones, and dilate pupil to a larger extent even under constant sound levels (Hersman et al., 2020; Liao, Kidani, et al., 2016), it is also possible, according to the inverse effectiveness principle, that pure tones are more suitable stimuli for studies to observe superadditive pupillary integration (e.g., in Rigato et al., 2016, compared to white noises in Van der Stoep et al., 2021 and the present study). But in one previous study which recruited macaque monkeys as subjects and used pure tones with flashes, researchers also reported a linear integration of pupillary responses (Wang et al., 2014).

There is another critical aspect in the study that reported superadditive pupillary integration (Rigato et al., 2016) should be noted. That is, no catch trials were included in this study when comparing the pupillary responses simultaneously evoked by auditory and visual stimuli (AV) and the synthetic pupillary responses by linear summation of the unisensory pupillary responses (A+V). As mentioned in the Section 2, this comparison would be unfair if the tonic pupil fluctuation (due to such as expectancy, arousal, or other factors) contained in the stimulus-induced pupillary responses is added twice. Therefore, the optimal strategy is to independently measure the tonic pupil fluctuation in the catch trials, and subtract it from the unisensory and multisensory pupillary responses before comparison. Otherwise, it is more likely to observe a nonlinear superadditive or subadditive summation than a linear additive summation. This concern was partially confirmed by Van der Stoep et al. (2021). They demonstrated in the response-blocks that the uncorrected pupil time series in response to multisensory signals are subadditive than their linear summation. We should, nonetheless, be cautious in interpreting a nonlinear pupillary integration without subtracting the tonic pupil fluctuation out.

Of particular interest, the temporal properties of the pupillary responses in previous studies that explored the nature of pupillary integration are inconsistent. In studies that revealed linear integration, the pupillary responses arose in a short latency and lasted for hundreds of milliseconds (Van der Stoep et al., 2021; Wang et al., 2014, 2017), whereas in the study that revealed nonlinear integration, the pupillary responses arose relatively slowly and sustained longer (Rigato et al., 2016). It seems that the integration of early, transient pupillary responses and the integration of late, sustained pupillary responses may differentiate from each other in nature. The early pupillary response (dilation), which

is typically evoked by the appearance of high-salient sensory stimuli, intimately relates to orienting (Strauch et al., 2022; Wang & Munoz, 2015). It also has a comparable latency with the pupillary light reflex (Clarke et al., 2003; Mathôt, 2018; Wang & Munoz, 2014). As the light-sensitive pupillary reflex is mainly controlled by the parasympathetic system, the early orienting-related pupillary responses may stem from parasympathetic inhibition (Marumo & Nakano, 2021; Steinhauer et al., 2022; Steinhauer & Hakerem, 1992; Widmann et al., 2018). This presumption is confirmed by a recent pharmacological study, which showed that this early pupil dilation (0.5–1.48 s after stimulus onset) can be eliminated when the parasympathetic activities are selectively blocked but does not significantly decrease when the sympathetic system is blocked (Marumo & Nakano, 2021). In comparison, the late and sustained pupillary response is potentially evoked through the sympathetic pathway by other intermediate- and high-level cognitive factors related to arousal and mental effort (Mathôt, 2018; Steinhauer & Hakerem, 1992; Widmann et al., 2018).

The current study, successfully separating the early orienting-related pupillary responses out of the pupil time series using a pupil oscillation paradigm, again found little evidence for a nonlinear pupillary integration. In addition, we concurrently revealed that the overall pupillary responses as measured by the mean pupil size across time is also linear additive. Because the overall pupillary responses are composed of both the early pupillary responses and other late pupillary responses, we deduce that the latter may be linear additive too. This is consistent with a recent study (Exp 2 in Van der Stoep et al., 2021), which did not find a superadditive integration of pupillary responses occurred after 1 s in an almost identical design with Rigato et al. (2016). Therefore, the pupillary responses, irrespective of whether they are related to orienting, arousal, mental effort or other cognitive factors and mediated by the parasympathetic and sympathetic pathways, may be linearly integrated and independent of each other, as long as they are not constrained by the extreme of normal pupil size.

It is noted that the multisensory integration process is characterized by large intraindividual variabilities (Cecere et al., 2015; Leonardelli et al., 2015; Murray et al., 2019; Yuan et al., 2016). The nature of pupillary integration may vary across trials within participants. It has been shown that pupillary responses are closely related to the tonic arousal state indicated by the BPS trial-by-trial; a larger BPS would eventually lead to a smaller pupillary response (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Murphy et al., 2011; van Kempen et al., 2019). Here, we also found the overall pupillary responses measured by the

mean pupil size were negatively predicted by the BPS, whereas the early pupillary responses measured by the oscillatory amplitude was not significantly modulated by the BPS. This further indicated that these two measures may reflect differential mechanisms, and it is the late, sustained pupillary responses that are possibly sensitive to the tonic arousal state. And consistent with Wang and Munoz (2014), the pupillary responses evoked by salient sound are insensitive to tonic arousal state. More importantly, the pupillary integration did not significantly change from additive to subadditive or superadditive as a function of the BPS. Given that larger BPS (heightened tonic arousal) relates to an exploration state (i.e., task disengagement) more than an exploitation state (i.e., task engagement) (Gilzenrat et al., 2010; Jepma & Nieuwenhuis, 2011), the results imply that pupillary integration may be immune to observers' cognitive states, and uniformly conforms to a linear additive algorithm.

At last, since the pupillary responses solely induced by visual saliency in the current study are inevitably mixed with or overshadowed by the strong light-sensitive pupillary reflex, our findings also contribute to revealing the integration between pupillary responses to luminance and other factors, here, the auditory saliency. A plenty of previous studies have explored the interaction between pupillary responses to luminance and arousal. Some of them showed that emotional or cognitive arousal-linked pupil dilation was larger in a dim compared with a bright background (Cherng et al., 2020; Pan et al., 2022; Peysakhovich et al., 2017, but see Steinhauer et al., 2004 for opposite results). Others, however, revealed no influence of background luminance on pupil dilation associated with arousal, particularly regarding to certain components (Widmann et al., 2018), for example, the phasic pupillary responses (Gilzenrat et al., 2010; Peysakhovich et al., 2017). A recent study endorsed this independence by demonstrating that the luminance- or cognitive arousal-linked baseline pupillary responses only affect the subsequent pupillary responses to the same inducer, with little interaction (Hu et al., 2022). Because there are so many factors to consider, such as the range of luminance, the specific task, and individual differences, it is currently challenging to reconcile the contradicting outcomes in the relationship between pupillary responses to luminance and arousal. Nonetheless, we could alter the light-sensitive parasympathetic activities by manipulating the background luminance, making it a low-cost approach to differentiate the contributions of the parasympathetic and sympathetic pathways to the arousal-linked pupillary responses (Cherng et al., 2020; Steinhauer et al., 2004, 2022; Widmann et al., 2018).

In conclusion, the current study illustrated that the pupillary responses evoked by multisensory signals may

be linear additive, and this additive nature of pupillary integration is not affected by the temporal properties of the pupillary responses, and the cognitive state of individual observers. Future studies can either manipulate the background luminance or pharmacologically block the activities of one pathway to directly test whether the pupillary responses regulated by the parasympathetic or the sympathetic pathway are linear additive. Additionally, it is encouraged for future studies to examine how the critical subcortical nuclei, for instance, the superior colliculus (Netser et al., 2010; Wang et al., 2014) and the locus coeruleus (Joshi et al., 2016), that modulate pupil size through the two autonomic nervous pathways, are involved in the linear integration of pupillary responses.

## AUTHOR CONTRIBUTIONS

**Wenjie Liu:** Data curation; formal analysis; writing – original draft; writing – review and editing. **Yuhui Cheng:** Formal analysis; writing – review and editing. **Xiangyong Yuan:** Conceptualization; methodology; supervision; writing – original draft; writing – review and editing. **Yi Jiang:** Funding acquisition; methodology; supervision; writing – review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no competing interest.

## DATA AVAILABILITY STATEMENT

All data have been made publicly available via the Institutional Knowledge Repository, Institute of Psychology, Chinese Academy of Sciences, and can be accessed at <http://ir.psych.ac.cn/handle/311026/44282>.

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## REFERENCES

- Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, 28, 403–450. <https://doi.org/10.1146/annurev.neuro.28.061604.135709>
- Brainard, D. (1997). The psychophysics toolbox. *Spatial Vision*, 10, 433–436. <https://doi.org/10.1163/156856897X00357>
- Calvert, G. A., & Thesen, T. (2004). Multisensory integration: Methodological approaches and emerging principles in the human brain. *Journal of Physiology-Paris*, 98(1–3), 191–205. <https://doi.org/10.1016/j.jphysparis.2004.03.018>
- Cecere, R., Rees, G., & Romei, V. (2015). Individual differences in alpha frequency drive crossmodal illusory perception. *Current Biology*, 25(2), 231–235. <https://doi.org/10.1016/j.cub.2014.11.034>
- Cherng, Y.-G., Baird, T., Chen, J.-T., & Wang, C.-A. (2020). Background luminance effects on pupil size associated with emotion and saccade preparation. *Scientific Reports*, 10(1), 15718. <https://doi.org/10.1038/s41598-020-72954-z>
- Clarke, R. J., Zhang, H., & Gamlin, P. D. R. (2003). Characteristics of the pupillary light reflex in the alert rhesus monkey. *Journal of Neurophysiology*, 89(6), 3179–3189. <https://doi.org/10.1152/jn.01131.2002>
- Gilzenrat, M. S., Nieuwenhuis, S., Jepma, M., & Cohen, J. D. (2010). Pupil diameter tracks changes in control state predicted by the adaptive gain theory of locus coeruleus function. *Cognitive, Affective, & Behavioral Neuroscience*, 10(2), 252–269. <https://doi.org/10.3758/CABN.10.2.252>
- Hersman, S., Allen, D., Hashimoto, M., Brito, S. I., & Anthony, T. E. (2020). Stimulus salience determines defensive behaviors elicited by aversively conditioned serial compound auditory stimuli. *eLife*, 9, e53803. <https://doi.org/10.7554/eLife.53803>
- Hoeks, B., & Levelt, W. J. M. (1993). Pupillary dilation as a measure of attention: A quantitative system analysis. *Behavior Research Methods, Instruments, & Computers*, 25(1), 16–26. <https://doi.org/10.3758/BF03204445>
- Hu, X., Hisakata, R., & Kaneko, H. (2022). The relationship between pupillary baseline manipulated by mental effort or luminance and subsequent pupillary responses. *Journal of Vision*, 22(7), 7. <https://doi.org/10.1167/jov.22.7.7>
- Jepma, M., & Nieuwenhuis, S. (2011). Pupil diameter predicts changes in the exploration–exploitation trade-off: Evidence for the adaptive gain theory. *Journal of Cognitive Neuroscience*, 23(7), 1587–1596. <https://doi.org/10.1162/jocn.2010.21548>
- Joshi, S., & Gold, J. I. (2020). Pupil size as a window on neural substrates of cognition. *Trends in Cognitive Sciences*, 24(6), 466–480. <https://doi.org/10.1016/j.tics.2020.03.005>
- Joshi, S., Li, Y., Kalwani, R. M., & Gold, J. I. (2016). Relationships between pupil diameter and neuronal activity in the locus coeruleus, colliculi, and cingulate cortex. *Neuron*, 89(1), 221–234. <https://doi.org/10.1016/j.neuron.2015.11.028>
- Knapen, T., de Gee, J. W., Brascamp, J., Nuiten, S., Hoppenbrouwers, S., & Theeuwes, J. (2016). Cognitive and ocular factors jointly determine pupil responses under equiluminance. *PLoS One*, 11(5), e0155574. <https://doi.org/10.1371/journal.pone.0155574>
- Leonardelli, E., Braun, C., Weisz, N., Lithari, C., Occelli, V., & Zampini, M. (2015). Prestimulus oscillatory alpha power and connectivity patterns predispose perceptual integration of an audio and a tactile stimulus. *Human Brain Mapping*, 36(9), 3486–3498. <https://doi.org/10.1002/hbm.22857>
- Liao, H.-I., Kidani, S., Yoneya, M., Kashino, M., & Furukawa, S. (2016). Correspondences among pupillary dilation response, subjective salience of sounds, and loudness. *Psychonomic Bulletin & Review*, 23(2), 412–425. <https://doi.org/10.3758/s13423-015-0898-0>

- Liao, H.-I., Yoneya, M., Kidani, S., Kashino, M., & Furukawa, S. (2016). Human pupillary dilation response to deviant auditory stimuli: Effects of stimulus properties and voluntary attention. *Frontiers in Neuroscience*, *10*(43), 1–14. <https://doi.org/10.3389/fnins.2016.00043>
- Marumo, C., & Nakano, T. (2021). Early phase of pupil dilation is mediated by the peripheral parasympathetic pathway. *Journal of Neurophysiology*, *126*(6), 2130–2137. <https://doi.org/10.1152/jn.00401.2021>
- Mathôt, S. (2018). Pupillometry: Psychology, physiology, and function. *Journal of Cognition*, *1*(1), 16. <https://doi.org/10.5334/joc.18>
- Murphy, P. R., Robertson, I. H., Balsters, J. H., & O'Connell, R. G. (2011). Pupillometry and P3 index the locus coeruleus–noradrenergic arousal function in humans. *Psychophysiology*, *48*(11), 1532–1543. <https://doi.org/10.1111/j.1469-8986.2011.01226.x>
- Murray, M. M., Thelen, A., Ionta, S., & Wallace, M. T. (2019). Contributions of intraindividual and interindividual differences to multisensory processes. *Journal of Cognitive Neuroscience*, *31*(3), 360–376. [https://doi.org/10.1162/jocn\\_a\\_01246](https://doi.org/10.1162/jocn_a_01246)
- Naber, M., Alvarez, G. A., & Nakayama, K. (2013). Tracking the allocation of attention using human pupillary oscillations. *Frontiers in Psychology*, *4*, 1–12. <https://doi.org/10.3389/fpsyg.2013.00919>
- Netser, S., Ohayon, S., & Gutfreund, Y. (2010). Multiple manifestations of microstimulation in the optic tectum: Eye movements, pupil dilations, and sensory priming. *Journal of Neurophysiology*, *104*(1), 108–118. <https://doi.org/10.1152/jn.01142.2009>
- Noesselt, T., Tyll, S., Boehler, C. N., Budinger, E., Heinze, H.-J., & Driver, J. (2010). Sound-induced enhancement of low-intensity vision: Multisensory influences on human sensory-specific cortices and thalamic bodies relate to perceptual enhancement of visual detection sensitivity. *The Journal of Neuroscience*, *30*(41), 13609–13623. <https://doi.org/10.1523/jneurosci.4524-09.2010>
- Pan, J., Klímová, M., McGuire, J. T., & Ling, S. (2022). Arousal-based pupil modulation is dictated by luminance. *Scientific Reports*, *12*(1), 1390. <https://doi.org/10.1038/s41598-022-05280-1>
- Pelli, D. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442. <https://doi.org/10.1163/156856897X00366>
- Peysakhovich, V., Vachon, F., & Dehais, F. (2017). The impact of luminance on tonic and phasic pupillary responses to sustained cognitive load. *International Journal of Psychophysiology*, *112*, 40–45. <https://doi.org/10.1016/j.ijpsycho.2016.12.003>
- Rigato, S., Rieger, G., & Romei, V. (2016). Multisensory signalling enhances pupil dilation. *Scientific Reports*, *6*, 26188. <https://doi.org/10.1038/srep26188>
- Şahin, M. D., & Aybek, E. C. (2019). Jamovi: An easy to use statistical software for the social scientists. *International Journal of Assessment Tools in Education*, *6*, 670–692. <https://doi.org/10.21449/ijate.661803>
- Schwiedrzik, C. M., & Sudmann, S. S. (2020). Pupil diameter tracks statistical structure in the environment to increase visual sensitivity. *The Journal of Neuroscience*, *40*(23), 4565–4575. <https://doi.org/10.1523/jneurosci.0216-20.2020>
- Senkowski, D., Saint-Amour, D., Höfle, M., & Foxe, J. J. (2011). Multisensory interactions in early evoked brain activity follow the principle of inverse effectiveness. *NeuroImage*, *56*(4), 2200–2208. <https://doi.org/10.1016/j.neuroimage.2011.03.075>
- Stein, B. E., Stanford, T. R., & Rowland, B. A. (2020). Multisensory integration and the society for neuroscience: Then and now. *The Journal of Neuroscience*, *40*(1), 3–11. <https://doi.org/10.1523/jneurosci.0737-19.2019>
- Steiner, G. Z., & Barry, R. J. (2011). Pupillary responses and event-related potentials as indices of the orienting reflex. *Psychophysiology*, *48*(12), 1648–1655. <https://doi.org/10.1111/j.1469-8986.2011.01271.x>
- Steinhauer, S. R., Bradley, M. M., Siegle, G. J., Roeklein, K. A., & Dix, A. (2022). Publication guidelines and recommendations for pupillary measurement in psychophysiological studies. *Psychophysiology*, *59*(4), e14035. <https://doi.org/10.1111/psyp.14035>
- Steinhauer, S. R., & Hakerem, G. (1992). The pupillary response in cognitive psychophysiology and schizophrenia. *Annals of the New York Academy of Sciences*, *658*(1), 182–204. <https://doi.org/10.1111/j.1749-6632.1992.tb22845.x>
- Steinhauer, S. R., Siegle, G. J., Condray, R., & Pless, M. (2004). Sympathetic and parasympathetic innervation of pupillary dilation during sustained processing. *International Journal of Psychophysiology*, *52*(1), 77–86. <https://doi.org/10.1016/j.ijpsycho.2003.12.005>
- Stevenson, R. A., & James, T. W. (2009). Audiovisual integration in human superior temporal sulcus: Inverse effectiveness and the neural processing of speech and object recognition. *NeuroImage*, *44*(3), 1210–1223. <https://doi.org/10.1016/j.neuroimage.2008.09.034>
- Strauch, C., Wang, C.-A., Einhäuser, W., Van der Stigchel, S., & Naber, M. (2022). Pupillometry as an integrated readout of distinct attentional networks. *Trends in Neurosciences*, *45*(8), 635–647. <https://doi.org/10.1016/j.tins.2022.05.003>
- Van der Stoep, N., Van der Smagt, M. J., Notaro, C., Spock, Z., & Naber, M. (2021). The additive nature of the human multisensory evoked pupil response. *Scientific Reports*, *11*(1), 707. <https://doi.org/10.1038/s41598-020-80286-1>
- van Kempen, J., Loughnane, G. M., Newman, D. P., Kelly, S. P., Thiele, A., O'Connell, R. G., & Bellgrove, M. A. (2019). Behavioural and neural signatures of perceptual decision-making are modulated by pupil-linked arousal. *eLife*, *8*, e42541. <https://doi.org/10.7554/eLife.42541>
- Wang, C.-A., Blohm, G., Huang, J., Boehnke, S. E., & Munoz, D. P. (2017). Multisensory integration in orienting behavior: Pupil size, microsaccades, and saccades. *Biological Psychology*, *129*(Supplement C), 36–44. <https://doi.org/10.1016/j.biopsycho.2017.07.024>
- Wang, C.-A., Boehnke, S. E., Itti, L., & Munoz, D. P. (2014). Transient pupil response is modulated by contrast-based saliency. *The Journal of Neuroscience*, *34*(2), 408–417. <https://doi.org/10.1523/jneurosci.3550-13.2014>
- Wang, C.-A., & Munoz, D. P. (2014). Modulation of stimulus contrast on the human pupil orienting response. *European Journal of Neuroscience*, *40*(5), 2822–2832. <https://doi.org/10.1111/ejn.12641>
- Wang, C.-A., & Munoz, D. P. (2015). A circuit for pupil orienting responses: Implications for cognitive modulation of pupil size. *Current Opinion in Neurobiology*, *33*, 134–140. <https://doi.org/10.1016/j.conb.2015.03.018>
- Werner, S., & Noppeney, U. (2010). Superadditive responses in superior temporal sulcus predict audiovisual benefits in object categorization. *Cerebral Cortex*, *20*(8), 1829–1842. <https://doi.org/10.1093/cercor/bhp248>

- Widmann, A., Schröger, E., & Wetzels, N. (2018). Emotion lies in the eye of the listener: Emotional arousal to novel sounds is reflected in the sympathetic contribution to the pupil dilation response and the P3. *Biological Psychology*, *133*, 10–17. <https://doi.org/10.1016/j.biopsycho.2018.01.010>
- Yuan, X., Cheng, Y., & Jiang, Y. (2021). Multisensory signals inhibit pupillary light reflex: Evidence from pupil oscillation. *Psychophysiology*, *58*(8), e13848. <https://doi.org/10.1111/psyp.13848>
- Yuan, X., Li, H., Liu, P., Yuan, H., & Huang, X. (2016). Pre-stimulus beta and gamma oscillatory power predicts perceived audiovisual simultaneity. *International Journal of Psychophysiology*, *107*, 29–36. <https://doi.org/10.1016/j.ijpsycho.2016.06.017>
- Zhao, S., Chait, M., Dick, F., Dayan, P., Furukawa, S., & Liao, H.-I. (2019). Pupil-linked phasic arousal evoked by violation but not

emergence of regularity within rapid sound sequences. *Nature Communications*, *10*(1), 4030. <https://doi.org/10.1038/s41467-019-12048-1>

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