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Pupillometry Analysis of Rapid Serial Visual Presentation at Five Presentation Rates

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Abstract: In this study, the effect of presentation rates on pupil dilation is investigated for target recognition in the Rapid Serial Visual Presentation (RSVP) paradigm. In this experiment, the RSVP paradigm with five different presentation rates, including 50, 80, 100, 150, and 200 ms, is designed. The pupillometry data of 15 subjects are collected and analyzed. The pupillometry results reveal that the peak and average amplitudes for pupil size and velocity at the 80-ms presentation rate are considerably higher than those at other presentation rates. The average amplitude of pupil acceleration at the 80-ms presentation rate is significantly higher than those at the other presentation rates. The latencies under 50- and 80-ms presentation rates are considerably lower than those of 100-, 150-, and 200-ms presentation rates. Additionally, no considerable differences are observed in the peak, average amplitude, and latency of pupil size, pupil velocity, and acceleration under 100-, 150-, and 200-ms presentation rates. These results reveal that with the increase in the presentation rate, pupil dilation first increases, then decreases, and later reaches saturation. The 80-ms presentation rate results in the largest point of pupil dilation. No correlation is observed between pupil dilation and recognition accuracy under the five presentation rates.

Key words: pupil dilation; presentation rate; Rapid Serial Visual Presentation (RSVP)

1 Introduction

With the development of eye trackers, the accompanying high temporal resolution and precision promotes cognitive studies on target recognition. Pupil dilation is related to the cognitive processing of visual information, such as attention, memory, and cognitive load[1−3]. The inhibition of the parasympathetic nervous system and Edinger-Westphal is involved in pupil dilation[4, 5]. These inhibitory processes are carried out by the Locus Coeruleus-Norepinephrine (namely LC-NE) system, which is in charge of the regulation of attention. Given that the pupil can expand significantly when the target image is gazed at, pupil dilation has a broad application prospect in target recognition.

In recent years, researchers conduct many studies on pupil dilation in different tasks, such as n-back[6, 7], digital span[8, 9], conflict[10, 11], and Rapid Serial Visual Presentation (RSVP) tasks[12, 13]. For the n-back task, many experiments indicate that pupil dilation increases with the increase in n[6, 7]. For the digital span task, several studies show that the pupil dilates as the number n increases[8, 9]. For the conflict task, many studies demonstrate that the pupil dilation of the non-conflict trial is significantly greater than that of the conflict trial[10, 11]. For the RSVP task, Privitera et al.[12] analyzed the effect of target probability and

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button press on pupil dilation. The results show that the lower the target probability, the greater the pupil dilation. In addition, pupil dilation with a button press is significantly greater than that without one. Chen et al.[13] observed that pupil dilation of hidden identity information is significantly greater than that of irrelevant information.

The above studies reveal that cognitive load can lead to changes in pupil dilation in different tasks. In the RSVP paradigm, some parameters of RSVP, such as target probability[12], button press[12], and task difficulty[6–9], affect pupil dilation. Meanwhile, the presentation rate is a key parameter of the RSVP task. In the Brain-Computer Interface (BCI) field, many EEG studies focus on the presentation rate of stimuli from 50 ms to 500 ms in the RSVP task[14–16]. The results show that the presentation rate between 100 ms–200 ms can balance the classification accuracy and presentation rate to maximize the performance of RSVP-BCI[17]. However, no pupillometry studies is conducted on the extent of pupil dilation at different presentation rates. Therefore, the effect of presentation rates on pupil dilation in the target recognition task must be investigated.

As mentioned above, pupil dilation is analyzed at five presentation rates in the RSVP task. This study collects and analyzes the pupillometry data of 15 university students at five presentation rates. For the organization of this study, Section 2 presents the experimental procedure and data processing, Section 3 details the pupillometry results, and Section 4 discusses the results.

2 Method

2.1 Participants

A total of 15 right-handed university students (3 females, 12 males; 20–22 years old) participated in the experiment. All subjects had no history of neurological disease or mental disorders, and had normal vision or corrected to normal vision. This experiment was approved by the local ethics committee and conducted in accordance with the Declaration of Helsinki. All subjects signed a consent form before the experiments and received financial rewards afterward.

2.2 Materials

Images are obtained from the morgueFile database[18], and their brightness is normalized. Meanwhile, all image stimuli are made into videos using Adobe Premiere software, and all images are set to the same parameters of brightness. In addition, all stimuli are scaled to 560 pixel $\times$ 360 pixel (width $\times$ height), and the target images are dalmatians and sunflowers[19].

Five different presentation rates are used: 50, 80, 100, 150, and 200 ms. For each presentation rate, 15 video stimuli have a time length of 9–12 s. The target probability is 1.5%–2% for the five presentation rates in RSVP tasks. For the 50-ms presentation rate, each video contains 200 images with three target images. For the 80-ms presentation rate, each video contains 150 pictures with three target pictures. For the 100-ms presentation rate, each video contains 100 images with two target pictures. For the 150-ms presentation rate, each video contained 60 pictures with 1 or 2 target images. For the 200-ms presentation rate, each video contains 50 pictures with a target picture. In consideration of attention blink and data extraction, the target pictures are placed at approximately 2 s after the onset and before the end of the stimulus. The interval between the two target images is at least longer than 2 s.

The five presentation rates of videos are verified by a photodetector. Alternating black and white images with corresponding presentation rates are made into videos using Adobe Premiere software. The photodetector is placed in a Virtual Reality (VR) headset with a 90 Hz refresh rate. The photodetector waveforms are collected by an electroencephalogram (EEG) amplifier with a sampling rate of 1000. Figure 1 shows the photodetector waveforms and their frequency for the five presentation rates. The results of Fast Fourier Transform (FFT) for 50-, 80-, 100-, 150-, and 200-ms presentation rates are 10.02, 6.28, 4.97, 3.34, and 2.02 Hz, respectively. Given the alternating flickering of black and white images, the frequencies of video display are twice as much as the FFT results. The corresponding presentation rates are 48.54, 79.49, 100.60, 149.70, and 198.40 ms. These results are close to the experimental requirements.

2.3 Experiment procedure

The subjects seat on comfortable chairs in a soundproof room. The experiment includes three sessions in total, and each session has 25 blocks. For each block, the prompt of target information is first displayed for 2 s at the center of the VR headset, and a white cross "+" is randomly present for 200–300 ms. Next, a video stimulus under the five presentation rates is randomly selected and displayed. If subjects detect the target picture, they are required to press the button as soon as possible and avoid blinking during the video stimuli.

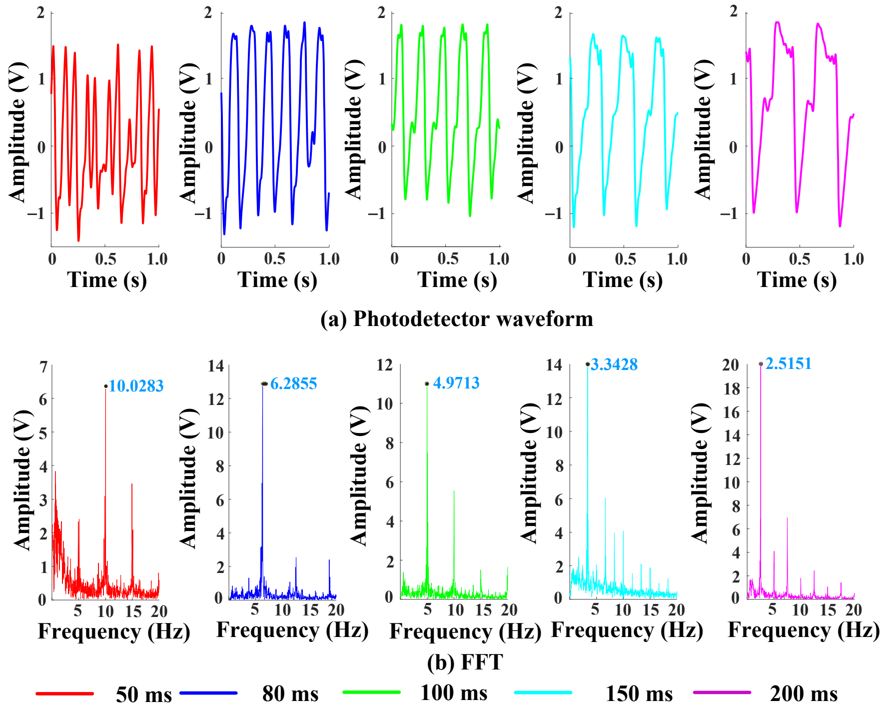

Fig. 1 Photodetector waveforms and their frequency at five presentation rates: 50, 80, 100, 150, and 200 ms.

Afterward, a black screen is kept on for 2 s. Then, the next block is entered. The subjects have a 3 min rest for every five blocks. The subjects rest for 10 min in each session. Figure 2 shows the whole experimental procedure.

2.4 Data recording and analysis

Pupillometry data are recorded using an embedded infrared eye-tracking module: aGlass DKII at a sampling rate of 120 Hz. Pupillometry is segmented from 1000 ms before the target onset to 2500 ms after the target onset, with the time window of 1000 ms before the target onset as the baseline. In addition, the time windows for the analysis of pupil dilation, pupil velocity, and pupil acceleration are determined based on a certain period before and after their latencies. The left and right pupillometry data are averaged. The pupillometry data contaminated by excessive blinking and head movements are removed manually. In a trial, some missing pupillometry data caused by blinking or other artifacts are filled in using previous data. Only pupillometry data with accurate target recognition are used in the analysis. Finally, the effective remaining pupillometry trials are equivalent under the five presentation rates.

Repeated-measures ANOVA is used to analyze the behavioral and pupillometry results. Pairwise comparisons are tested using the least-significant difference. The Greenhouse Geisser method is adopted to correct the statistical effect.

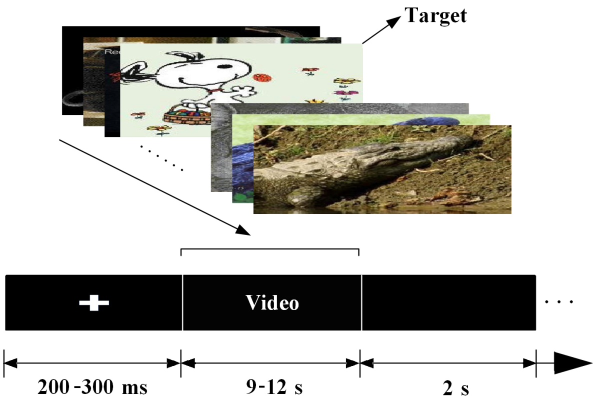

Fig. 2 Experiment procedure.

3 Result

3.1 Behavioral results

Previous studies showed that the reaction time of the button was within 300–550 ms[12]. Therefore, an inaccurate recognition is considered when the subject press the button for more than 1 s after the target onset. Figure 3 shows the recognition accuracy of the subjects at the presentation rates of 50, 80, 100, 150, and 200 ms. Repeated-measures ANOVA shows the main effect on the recognition accuracy under the different presentation rates ($F(4,56) = 124.358$, $p = 0.000$). Pairwise comparisons show that the 50 ms accuracy

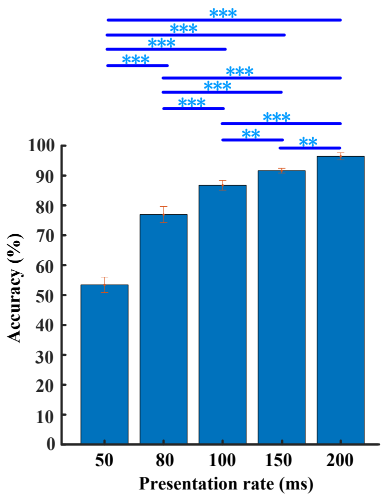

Fig. 3 Behavioral results. Error bars stand for standard deviation. ** denotes p<0.01 and * denotes p<0.001.**

is significantly lower (ps < 0.001), and the 200 ms accuracy is significantly higher (ps < 0.01) than those of other presentation rates. The results indicate that as the presentation rate increases, the recognition accuracy increases, and the difficulty of cognitive tasks decreases.

3.2 Pupillometry results

Figure 4 shows the pupil sizes of pupil dilation for all subjects (sub1–sub15) at five presentation rates of 50, 80, 100, 150, and 200 ms. Most subjects have a shorter latency of pupil dilation under the 50- and 80-ms presentation rates. In addition, the pupil sizes of the targets are larger than those of non-targets for each subject. Figure 5 shows the grand average pupil sizes of pupil dilation with five presentation rates of 50, 80, 100, 150, and 200 ms. The pupil size of the target picture is significantly larger than that of the non-target image for each presentation rate. The pupil size observed under the 80-ms presentation rate is the largest, and the latencies under the 50- and 80-ms presentation rates are shorter than those under the other rates.

Figure 6 shows the peaks, average amplitudes, and latencies for pupil dilation in the time window of 500–1500 ms at five presentation rates. The latencies of pupil dilation under the 50-, 80-, 100-, 150-, and 200-ms presentation rates are 877, 857, 1125, 1156, and 1176 ms, respectively.

Repeated-measures ANOVA shows the main effect on the peak of pupil dilation at five presentation rates (F (4, 56) = 3.779, p = 0.000). Pairwise comparisons reveal that the peak under the 80-ms presentation rate is

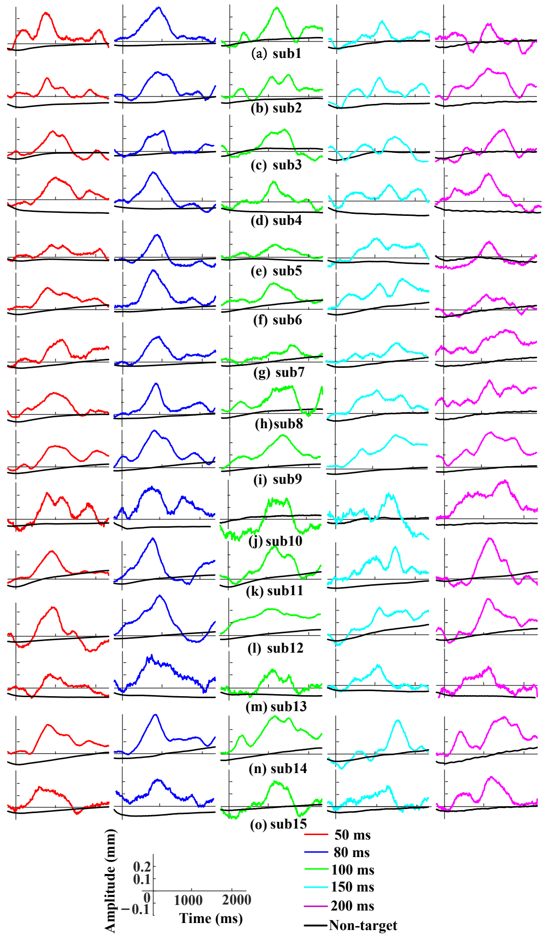

Fig. 4 Pupil sizes of pupil dilation in all subjects at five presentation rates of 50, 80, 100, 150, and 200 ms.

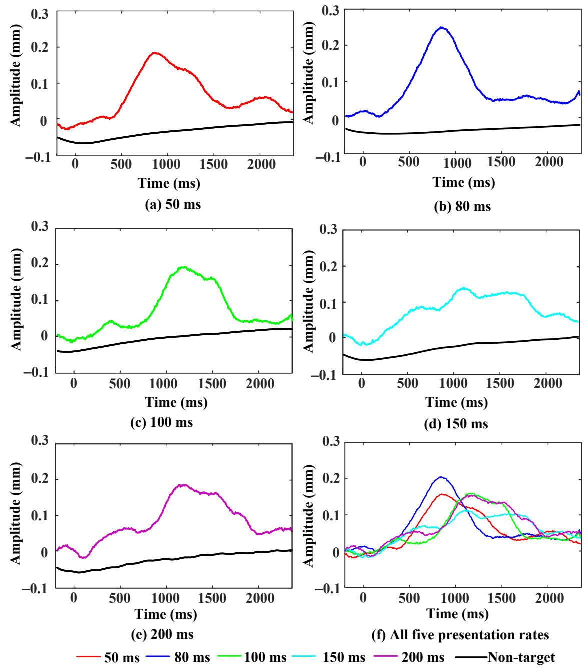

Fig. 5 Grand average pupil sizes of pupil dilation at five presentation rates of 50, 80, 100, 150, and 200 ms.

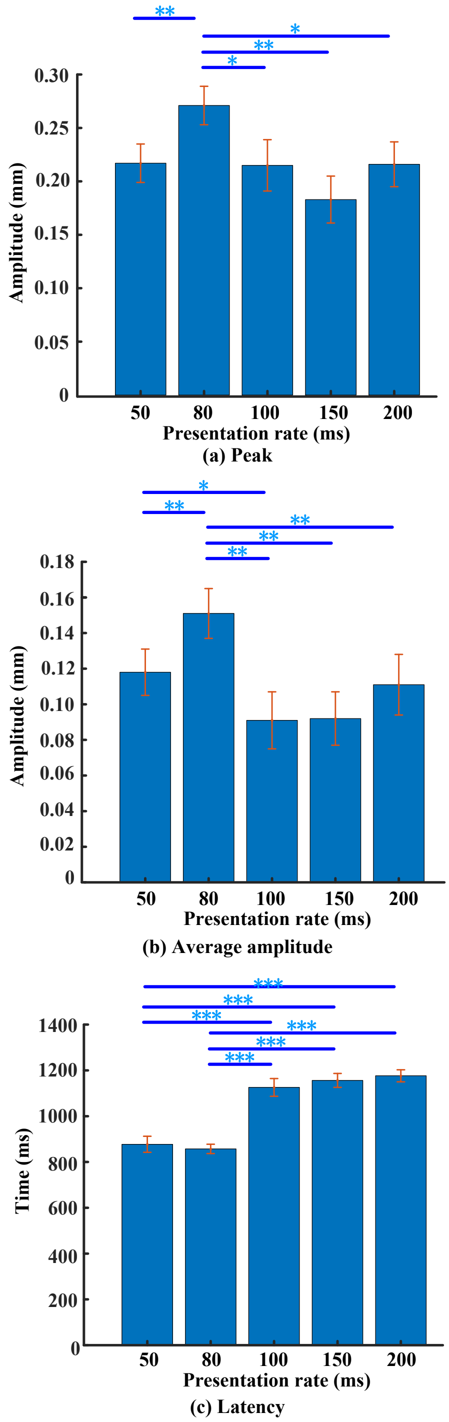

Fig. 6 Peaks, average amplitudes, and latencies of pupil dilation in the time window of 500–1500 ms at five presentation rates. Error bars stand for standard deviations. * denotes p<0.05, ** denotes p<0.01, and * denotes p<0.001.**

significantly higher than those observed with the other rates (*ps* < 0.001), and no significant differences is found among the peaks under the 50-, 100-, 150-, and 200-ms presentation rates (*ps* > 0.05).

Repeated-measures ANOVA shows the main effect on the average amplitude of pupil dilation at five presentation rates (F (4, 56) = 4.383, p = 0.000). Pairwise comparisons reveal that the average amplitude of the 80-ms presentation rate is significantly higher than those of the other rates (*ps* < 0.05), and the average amplitude of the 50-ms presentation rate is significantly higher than that of the 100-ms presentation rate ($p < 0.05$). No significant differences in the average amplitudes is found under the 100-, 150-, and 200-ms presentation rates (*ps* > 0.05).

Repeated-measures ANOVA of presentation rates shows a main effect on the latency of pupil dilation at five presentation rates (F (4, 56) = 30.24, p = 0.000). Subsequent pairwise comparisons show that the latencies of the 50- and 80-ms presentation rates are significantly shorter than those of the other rates (*ps* < 0.05), and no significant difference is observed in latency between the 50- and 80-ms presentation rates ($p > 0.05$). In addition, no significant differences is detected in the latencies under the 100-, 150-, and 200-ms presentation rates (*ps* > 0.05).

Figure 7 shows the peaks, average amplitudes, and latencies of pupil velocity in the time window of 500–1500 ms at five presentation rates. The latencies of pupil velocity at 50, 80, 100, 150, and 200 ms are 845, 788, 1076, 1062, and 1082 ms, respectively.

Repeated-measures ANOVA shows a main effect on the peak of pupil velocity at five presentation rates (F (4, 56) = 34.512, p = 0.000). Pairwise comparisons reveal that the peaks of 50- and 80-ms presentation rates are significantly higher than those of the other rates (*ps* $<$ 0.05), and no significant difference is found in the peaks between the 50 and 80-ms presentation rates ($p > 0.05$). In addition, no significant differences is observed among the peaks under the 100-, 150-, and 200-ms presentation rates (*ps* > 0.05).

Repeated-measures ANOVA shows a main effect on the average amplitude of pupil velocity at five presentation rates (F(4, 56) = 7.655, p = 0.000). Pairwise comparisons reveal that the average amplitudes of 50- and 80-ms presentation rates are significantly higher than those of the others (*ps* < 0.05), and the average amplitude of the 80-ms presentation rate is significantly higher than the 50-ms presentation rate ($p < 0.01$). No significant differences in the average amplitudes is found under the 100-, 150-, and 200-ms presentation rates (*ps* > 0.05).

Repeated-measures ANOVA of presentation rates shows that a main effect is observed on the latency of

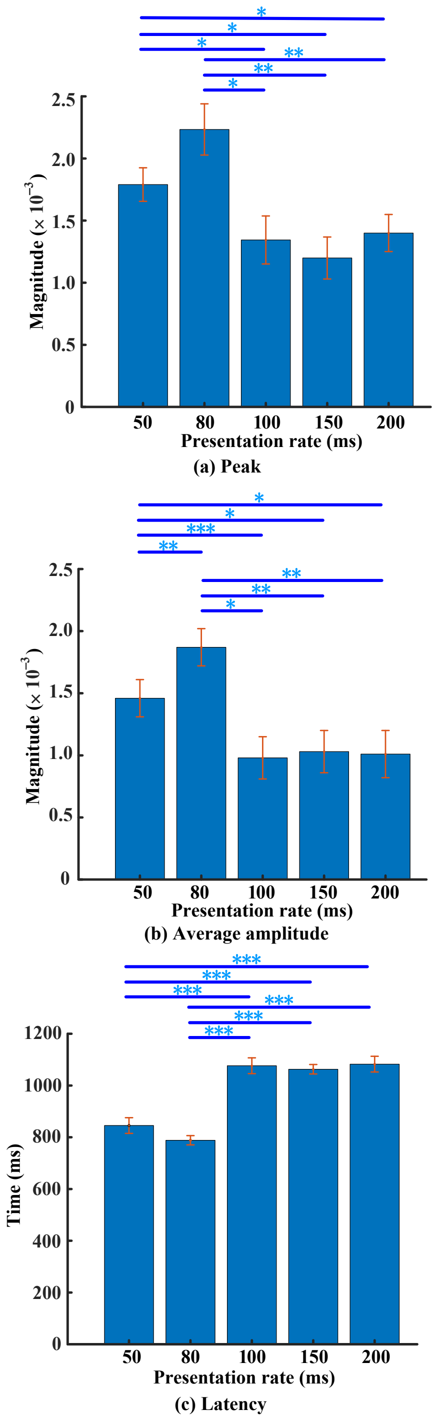

Fig. 7 Peaks, average amplitudes, and latencies of pupil velocity in the time window of 500–1500 ms at five presentation rates. Error bar stands for standard deviations. * denotes p<0.05, ** denotes p<0.01, and * denotes p<0.001.**

pupil velocity at five presentation rates (F (4, 56) = 34.512, p = 0.000). Subsequent pairwise comparisons reveal that the latencies in the 50- and 80-ms presentation rates are significantly shorter than those in the other rates (ps < 0.001), and no significant differences are found in the latencies between the 50- and 80-ms presentation rates (p > 0.05). In addition, no significant differences is noticed in the latencies under the 100-, 150-, and 200-ms presentation rates (ps > 0.05).

Figure 8 shows the peaks, average amplitudes, and latencies of pupil acceleration in the time window of

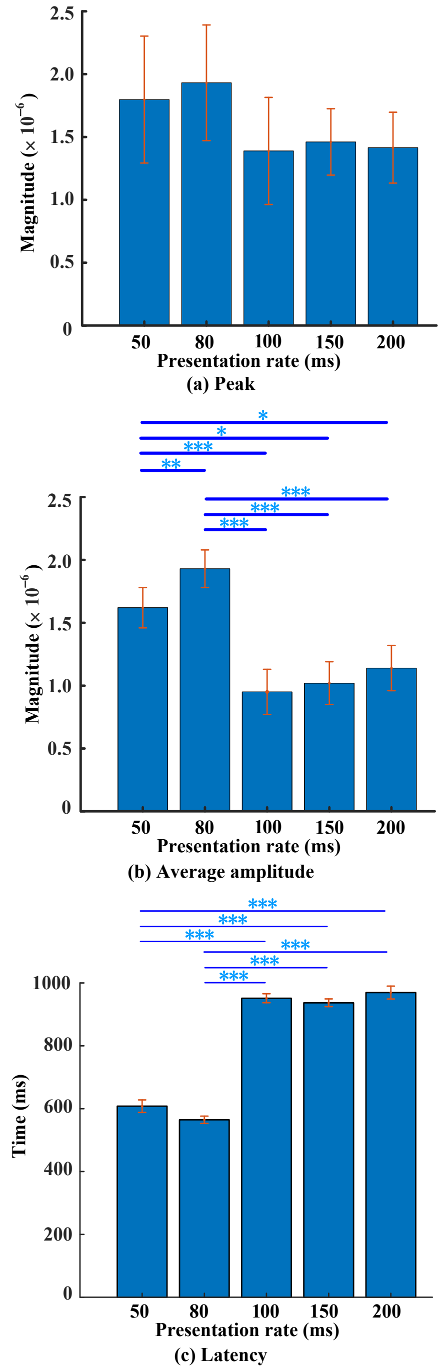

Fig. 8 Peaks, average amplitudes, and latencies of pupil acceleration in the time window of 500–1100 ms at five presentation rates. Error bar stands for standard deviations. * denotes p<0.05, ** denotes p<0.01, and * denotes p<0.001.**

500–1100 ms at five presentation rates. The latencies of pupil acceleration under the 50-, 80-, 100-, 150-, and 200-ms presentation rates are 608, 564, 951, 936, and 969 ms, respectively.

Repeated-measures ANOVA shows that no main effect is observed on the peak of pupil acceleration at the five presentation rates (F (4, 56) = 0.376, p = 0.824).

Repeated-measures ANOVA indicates that a main effect is detected on the average amplitude of pupil acceleration at five presentation rates (F (4, 56) = 13.679, p = 0.000). Pairwise comparisons reveal that the average amplitude of the 50- and 80-ms presentation rates are significantly higher than those of the other rates (ps < 0.05), and no significant difference is found in the latencies between the 50- and 80-ms presentation rates (p > 0.05). In addition, no significant differences is found among the average amplitudes of the 100-, 150-, and 200-ms presentation rates (ps > 0.05).

Repeated-measures ANOVA of presentation rates shows a main effect on the latency of pupil acceleration at the five presentation rates (F (4, 56) = 18.978, p = 0.000). Subsequent pairwise comparisons reveal that the latencies of the 50- and 80-ms presentation rates are significantly shorter than those of the others (ps < 0.001), and no significant difference is found in the latencies between 50- and 80-ms presentation rates (p > 0.05). Moreover, no significant differences is observed in the latencies under the 100-, 150-, and 200-ms presentation rates (ps > 0.05).

3.3 Correlation analysis between recognition accuracy and pupil dilation

Table 1 shows the correlation between pupil dilation and recognition accuracy at the five presentation rates. The results show that the peaks, average amplitudes, latencies of pupil size, pupil velocity, and pupil acceleration have no correlation with recognition accuracy.

3.4 Classification performance at five presentation rates

The average amplitudes of pupil dilation per 100 ms are used as features in the time window of 500–1500 ms for the five presentation rates. The non-target trials with the same number as the target trials are randomly selected. A total of 50% of trials are used for training, and the other 50% of trials are used for testing. Logistic regression is used for classification. Figure 9 shows the classification performance under the five presentation rates.

Repeated-measures ANOVA shows that a main effect is observed on the accuracy (ACC) values at the five presentation rates (F (4, 56) = 11.896, p = 0.000). Pairwise comparisons reveal a significantly higher ACC value of the 80-ms presentation rate compared with the other rates (ps < 0.05). In addition, the ACC value of the 50-ms presentation rate is significantly higher than those of the 100- and 200-ms presentation rates (ps < 0.01), and no significant difference is found in the ACC values between the 50- and 150-ms presentation rates (p > 0.05). Furthermore, the ACC value of the 150-ms presentation rate is significantly higher than those of the 100- and 200-ms presentation rates (ps < 0.05), and no significant difference is found in the ACC values between the 100- and 200-ms presentation rates (p > 0.05).

3.5 Behavioral results and cognitive load

In this study, the behavior results show that the recognition accuracy increases with the increase in the presentation rate from 50 to 200 ms. This finding indicates that as the presentation rate increases, the information perceived by the human brain increases. The human brain uses the increased perceived information to mobilize and integrate more cognitive resources for

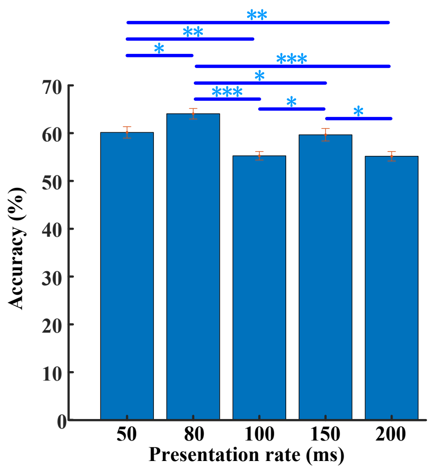

Fig. 9 Classification accuracy of the five presentation rates. Error bar stands for standard deviations. * denotes p<0.05, ** denotes p<0.01, and * denotes p<0.001.**

Table 1 Correlation between recognition accuracy and pupil dilation.

Item	Peak	Average amplitude	Latency
Pupil size	(r = − 0.300, p = 0.624)	(r = 0.589, p = 0.297)	(r = 0.923, p = 0.082
Pupil velocity	(r = − 0.669, p = 0.217)	(r = − 0.565, p = 0.296)	(r = 0.812, p = 0.095)
Pupil acceleration	(r = − 0.810, p = 0.097)	(r = − 0.658, p =0.227)	(r = 0.818, p = 0.090)

cognitive processing. Therefore, as the presentation rate increases, the cognitive load and recognition accuracy increase.

3.6 Behavioral and pupillometry results

In the pupillometry results, as the presentation rate increases from 50 to 200 ms, the peak, average amplitude, and latency of pupil size first increase, and then reach the maximum at the 80-ms presentation rate, next decrease, and later approach saturation. Therefore, with the increase in the presentation rate, the change in pupil dilation is inconsistent with that of recognition accuracy. In addition, the correlation analysis results show no correlation between the subjects' recognition accuracy and pupil dilation.

3.7 Pupil dilation and cognitive load

This study analyzes the effect of presentation rates on pupil dilation in RSVP tasks. When the presentation rate changes from 50 to 80 ms, the pupil size increases. The results are consistent with those of previous studies[20–22]. Pupil dilation is related to cognitive load, and pupil size increases with the increase in cognitive load. In the digital span task, Heitz et al.[20] observed that the pupil size with a high span under a high cognitive load is larger than that with a low span. In the visual search task, Porter et al.[21] used the pupil size to investigate the processing effort of visual search. The results show that the pupil size of the difficult visual search with a higher cognitive load is significantly larger than that of the easy visual search. Just et al.[22] reported that complex sentences with a high cognitive load have a larger pupil size than simple sentences. Therefore, in this study, as cognitive load increases from 50- to 80-ms presentation rate, pupil dilation increases.

As the presentation rate increases to 100, 150, and 200 ms, the pupil size in pupil dilation decreases, the latency is prolonged, and both reach saturation afterward. The results are consistent with those of previous studies[23–25]. Thus, when cognitive load exceeds the processing ability of subjects, pupil dilation decreases. Poock[23] studied the effect of information processing on pupil size. The results show that pupil dilation decreases when the cognitive load exceeds the subject's processing effort. Granholm et al.[24] studied the relationship between pupil dilation and information processing load in the digital span task. The results show that under resource limitation, pupil dilation increases with the increase in cognitive load. However, when the available resource is exceeded, pupil dilation drops or does not increase anymore. Similarly, Pealver's research show that during information overload, pupil dilation decreases[25]. In this study, as the presentation rate increases from 80 to 200 ms, although the cognitive load increases with recognition accuracy, the change in pupil dilation is limited; that is, the pupil size first drops and then reaches saturation. The maximum pupil dilation is observed under the 80-ms presentation rate. In addition, a previous study show that pupil dilation is caused by the inhibition of the parasympathetic nervous system and Edinger-Westphal nucleus[4, 5], and the inhibition is controlled by the LC-NE system. Therefore, at the 80-ms presentation rate, the activation intensity of the LC-NE system may be greater than those under other presentation rates.

In addition, Koelewijn et al.[26] reported that the processing of two sentences results in a longer latency of pupil dilation compared with that of one sentence. Two sentences require a longer processing time than one sentence. In this study, the subjects perceive more information at 100-, 150-, and 200-ms presentation rates. Thus, the human brain uses the increased perceived information to mobilize and integrate more cognitive resources for cognitive processing, and a longer processing time is required. Meanwhile, the latency of pupil dilation is related to the excitement of the sympathetic nervous system[4, 5]. The greater the excitation of the sympathetic nervous system, the shorter the latency of pupil dilation. In this study, the fast presentation rates of 50 and 80 ms may cause greater excitation of the sympathetic nervous system compared with the 100-, 150-, and 200-ms presentation rates. Thus, a longer latency of pupil dilation is obtained. This study is a supplement to existing research. In addition, pupillometry analysis of more presentation rates will be studied in the future.

4 Conclusion

This study investigates the effect of presentation rates on pupil dilation in the RSVP task. In this experiment, the pupillometry data of 15 subjects are are collected in the RSVP paradigm at five different presentation rates (50, 80, 100, 150, and 200 ms). The peaks, average amplitudes and latencies of pupil size, pupil velocity, and pupil acceleration are analyzed. With the increase in the presentation rate, pupil dilation first increases, next decreases, and later reaches saturation. The 80-ms presentation rate results in the maximum pupil dilation. With the increase in the presentation rate, the change in pupil dilation is inconsistent with that of recognition accuracy. The results can provide useful and valuable references for target recognition.

Acknowledgment

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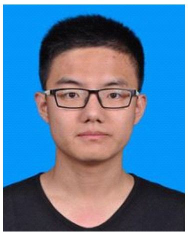

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