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Evidence that pupil dilation and cardiac afferent signalling differentially impact the processing of emotional intensity and racial bias

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ABSTRACT

Interoceptive cardiac arousal signals (e.g., from baroreceptor firing at ventricular systole compared to diastole) have been found to enhance perception of fearful versus neutral faces. They have also been found to amplify racially biased misidentification of tools as weapons when preceded by facial images of Black versus White individuals. Since pupil size is strongly coupled to arousal, we tested if experimental manipulation of pupil size influences fear processing in emotional judgement and racial bias tasks involving measurement of cardiac signals.

In a sample of 22 non-clinical participants in an emotional intensity judgement task, pupil size did not affect emotional intensity ratings. Nor did it interact with differential effects of cardiac systole versus diastole on intensity judgements of fearful and neutral faces, replicated here.

In a sample of 25 non-clinical participants in a weapons identification task, larger pupil size resulted in faster response times and lower accuracy when identifying tools and weapons. However, pupil size did not interact with weapon versus tool identification, race of prime, or cardiac timing. We nevertheless replicated the observed increase in racially biased misidentification of tools as weapons following Black face primes presented at cardiac systole.

Together our findings indicate that pupil dilation does not directly influence the processing of fear cues or perceived threat (as in racial bias) yet affects task performance by decreasing response times and accuracy. These findings contrast with the established effect of cardiac arousal signals on threat processing and may help focus interventions to mitigate related decision errors in high-pressure occupations.

KEYWORDS

pupil dilation; response time; accuracy; cardiac cycle; emotion processing

INTRODUCTION

Pupil size changes in response to three aspects of stimuli: they constrict in response to luminance, constrict in response to nearness, and dilate in response to increased arousal and mental effort (Mathôt, 2018). During threat or fear processing, pupil dilation occurs through sympathetic activation and is presumed to have an adaptive function (Bradley et al., 2008). Plausibly, wider pupils may bias vision toward salient information at lower spatial frequency (e.g. facial emotion versus identity) (Ebitz & Moore, 2019; Vuilleumier et al., 2003) and there is evidence that the neural representation of one's own pupil size may inform affective social interactions (Harrison et al., 2009; Harrison et al., 2006). However, there is a general paucity of data on the impact of pupil dilation on emotional processes. In contrast, cardiovascular arousal (Pezzulo et al., 2018) and afferent baroreceptor signalling (at ventricular systole) of the strength and timing of heartbeats (Garfinkel et al., 2021; Garfinkel et al., 2014) are known to influence the perception and processing of threat. Fearful stimuli are better detected and perceived to be more intense when presented at cardiac systole, compared to diastole, when baroreceptors are quiescent (Garfinkel et al., 2014). These phasic interoceptive signals concerning cardiovascular arousal impact fear memory (Garfinkel et al., 2021) and amplify social manifestations of fear and threat, not least the expression of stereotyped racial biases: the observed tendency for individuals to associate weapons (versus tools) more with Black than White individuals is amplified when faces are presented at cardiac systole (Azevedo et al., 2017). By extension, this suggests that tragic racially biased errors, e.g. in policing, may be more likely to occur if a law officer is in a state of heightened cardiovascular arousal induced by exertion or threat. Since pupil dilation typically accompanies systemic sympathetic arousal (Bradley et al., 2008; Wang et al., 2018), we sought clarity on whether pupil size influences threat processing and related racial bias.

We undertook an experimental study in which participants performed an emotional intensity judgement task (EIJT) and a weapons identification task (WIT) (Payne, 2001) during different pupillary conditions. In a within-participant design, each task was performed under four pupillary conditions designed to compare between a dilated and a non-dilated condition for both binocular and monocular vision. Monocular conditions were included to control for effects of binocular vision (e.g. stereopsis, binocular summation, and binocular rivalry). The EIJT assessed the participant's perceived intensity of fearful compared to neutral face images (Garfinkel et al., 2014). The WIT assessed implicit associations between Black males and weapons (Azevedo et al., 2017). Both tasks were synchronised with measurement of the participant's heartbeats so that certain stimuli (face images in EIJT, face primes in WIT) coincided with either ventricular systole or diastole. We hypothesized that pupil size would interact with emotional processing in these scenarios, potentially augmenting cardiac effects at systole through afferent arousal.

METHODS

Research ethics, governance, and study sample

The study, comprised of two different student projects conducted between 2019 and 2021, was approved by the Brighton and Sussex Medical School Research Governance and Ethics Committee. Participants aged 18 years and older were recruited through social media, poster advertisements placed across the University of Sussex campus, and lists of former participants who agreed to be contacted for future research. Exclusion criteria included having corrected vision or visual difficulty, being on medication (other than oral contraception), and having a self-declared history of or an ongoing medical, psychiatric, or neurodevelopmental condition.

Participants

For the emotional intensity judgement task (EIJT), there were 22 participants (mean age: 23.5 ± 3.6, 72.7% female, 77.3% Caucasian). For the weapons identification task (WIT), there were 25 participants (mean age: 23.5 ± 3.1, 64% female, 72% Caucasian). Fifteen participants performed both tasks. Response-time data collection was incomplete for one out of 25 participants. Accuracy data collection was incomplete for three out of 25 participants. These individuals were excluded from analyses.

Pupillary conditions

Both tasks were performed under four pupillary conditions: normal binocular (NB), shaded binocular vision (SB), normal monocular (NM), and mydriatic monocular (MM) vision. In the shaded binocular condition, participants wore sunglasses. In the normal monocular condition, the participant's non-dominant eye was occluded with an eyepatch. In the mydriatic monocular condition, the participant's non-dominant eye was occluded with an eyepatch and 1% Tropicamide eye drops were applied to the dominant eye. The first three conditions were counterbalanced, with the mydriatic monocular condition being performed last. Participants waited 15 minutes for the Tropicamide to take full effect before commencing the task. Mydriasis typically subsides within 4 to 8 hours, which ensured plenty of time for data collection (Hong & Tripathy, 2022). Each participant's pupil size was measured (in mm) once for each condition before the task commenced. This enabled the establishment of a baseline. Photos were taken using an iPhone7; 12-megapixel, f/1.8 and a Logitech C920 HD Pro.

Emotional processing and racial stereotype tasks

Emotional Intensity Judgement Task (EIJT). The participant rated the perceived emotional intensity of fearful and neutral faces taken from the Karolinska Directed Emotional Faces set (Lundqvist et al., 1998). Face stimuli were presented in a random sequence, shown for 100 ms and coinciding with either cardiac systole or diastole. Twenty fearful and 20 neutral faces were shown across 40 trials (10 per face-cardiac phase condition). Each stimulus was followed by a fixation cross lasting 150 ms, then a response preparation screen reading "Ready…" for 3–4 seconds. This was followed by a response screen reading "Go. How intense was that face?" and showing a visual analogue scale (VAS) from 0 ("Not intense at all") to 100 ("Maximally intense"). Participants used left and right arrow keys to provide their ratings by moving the centrally placed marker. A total of 4.5 seconds was provided for the response stage. The task was repeated for each of the four pupil conditions.

Weapons Identification Task (WIT). This task measured implicit associations between race and weapon identification, adapted from (Amodio, 2009; Azevedo et al., 2017; Payne, 2001). On each trial, a greyscale photograph drawn from a sample of 12 Black and 12 White male faces was presented as a 'prime' before a target stimulus from a set of images of tools (e.g. wrench, pliers) and handguns (Azevedo et al., 2017). Primes were presented for 200 ms coinciding with either cardiac systole or diastole. The target stimuli were then presented for 150 ms. A mask was presented before the prime and after the target for 600 and 300 ms, respectively. A variable intertrial interval (>4s) allowed predictive timing of the next cardiac phases. Participants were asked to click the right arrow key if they saw a weapon or the left arrow key if they saw a tool. Participants were instructed to be as fast and accurate as possible. Failure to respond within 500 ms would result in a warning message reading "Please be quicker". Data were collected for latencies up to 650 ms. Participants completed 120 trials (15 per face-object-cardiac phase condition) in each of the four pupil conditions. Accuracy was computed as the number of on-time correct responses divided by the number of valid trials.

Cardiac cycle monitoring

Medical-grade pulse oximetry (Nonin Xpod® 3012LP with soft finger mount) was used to monitor participants' heartbeats for timing stimuli to cardiac phase in the EIJT (Garfinkel et al., 2014). A pulse transit delay of 300 ms was used (Payne et al., 2006). In the WIT, three-lead ECG was used with electrodes placed in Einthoven's Triangle on the right arm to synchronise cardiac timing of facial prime stimuli (which preceded the target weapon or tool stimuli). Physiological waveforms were recorded on PC (power 1401, Spike2 v7 software; CED). Stimuli were presented just before the R-wave, corresponding to the end of diastole, or delayed by 300 ms from the R-wave peak, corresponding to peak systole. Stimuli timings were controlled using a real-time script on the CED-power1401 unit. Between task trials, a fixation cross was shown in the centre of the screen, during which four heartbeats (as detected by a QRS complex threshold) were recorded to predict the timing of the subsequent cardiac cycle.

Statistics

Bayesian repeated measures ANOVA in JASP (van den Bergh et al., 2022) was used to test for differences across pupillary conditions and interactions with remaining factors. Descriptive statistics are reported as mean ± SD. Effects are reported with Bayes Factors (BF) representing the likelihood ratio of the alternative to the null hypothesis. BFs > 3 indicate strong evidence for the alternative hypothesis, whereas BFs < 0.33 indicate strong evidence for the null hypothesis.

RESULTS

In the EIJT, pupil sizes differed across pupil conditions (NB = 2.82±0.91 mm, SB = 3.54±0.96 mm, NM = 4.18 ±1.10 mm, MM = 7.27±0.70 mm; BF=∞; Fig1A–B). There was no evidence of a main effect of pupil condition on emotional intensity ratings (BF=0.045; Fig1C–F; Table 1A). Pupil condition did not interact with fear condition (fearful versus neutral face; BF=0.030) or with cardiac phase (systole versus diastole; BF=0.006) in its influence on intensity ratings. Replicating previous work, there was evidence of an interaction between cardiac phase (systole versus diastole) and emotion intensity judgements for fearful versus neutral faces (BF=2890.16; Table 1A). Post hoc exploration showed relative preservation of fearful face intensity at systole while neutral faces were rated as less intense at systole compared to diastole (Garfinkel et al., 2014). This cardiac effect on emotion processing was not impacted by pupil condition (BF=6.6×10^{-4}; Fig 1D, Table 1A).

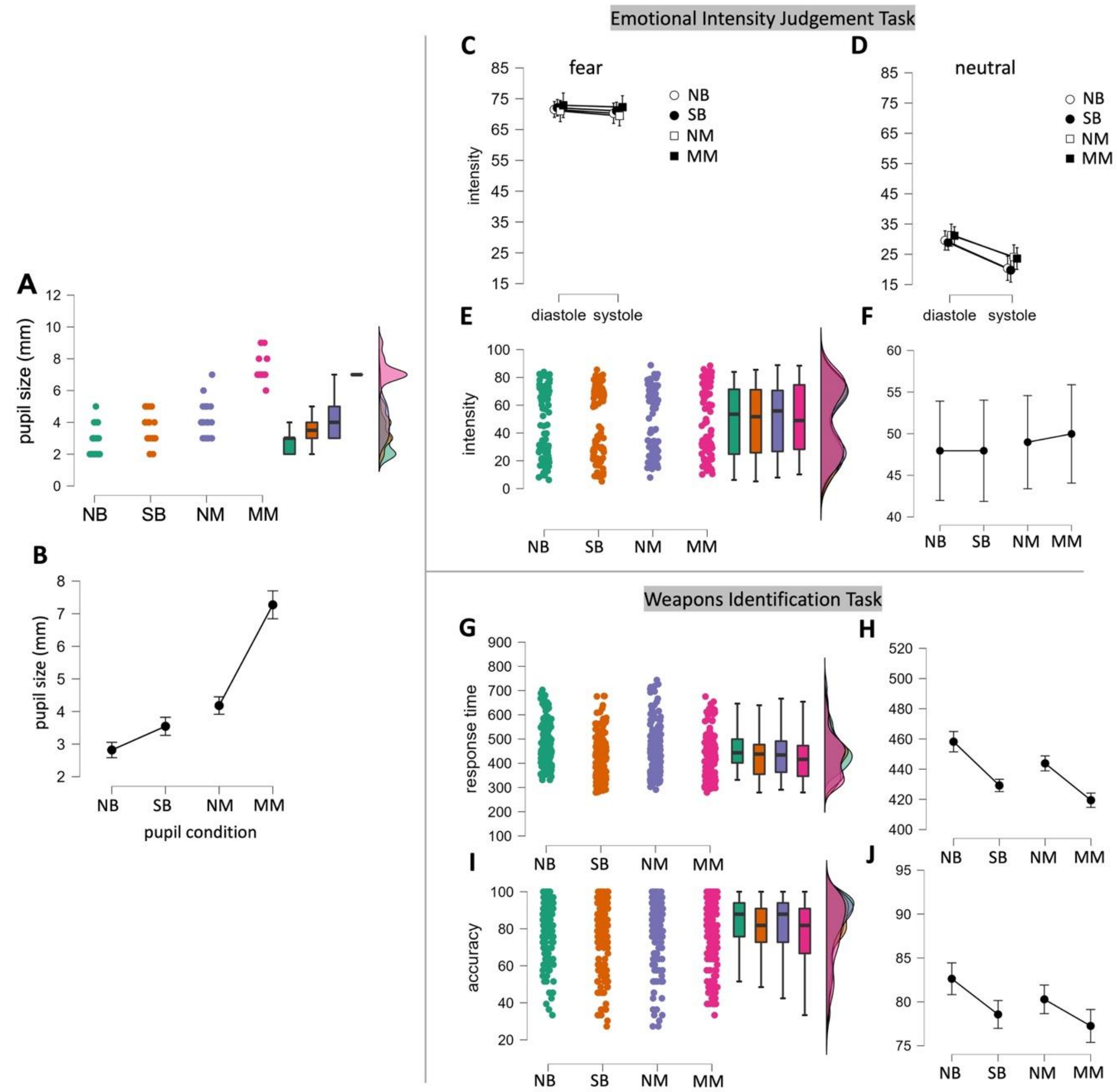

Fig 1. Pupil size and task performance under different pupillary conditions

(A-B) Pupil size increased across pupil conditions: normal binocular (NB), shaded binocular (SB), normal monocular (NM), and mydriatic monocular (MM). (C-F) Pupil condition did not influence intensity ratings. Pupil condition impacted response time (G-H) and accuracy (I-J). Distributions are shown as rainclouds, boxplots and half-violin plots. Black lines show means with 95% confidence intervals.

Table 1A. Selected Effects

Effects	P(incl)	P(excl)	P(incl|data)	P(excl|data)	BF_{incl}
pupil size	0.500	0.500	1.000	0.000	∞
Emotional Intensity Judgement Task					
pupil	0.737	0.263	0.112	0.888	0.045
cardiac phase ∗ condition	0.316	0.684	0.999	7.491e-4	2890.158

pupil ∗ cardiac phase ∗ condition	0.053	0.947	3.666e-5	1.000	6.599e-4
Weapons Identification Task – response time					
pupil	0.886	0.114	1.000	6.772e-15	1.896e+13
cardiac phase ∗ race ∗ object	0.120	0.880	0.767	0.233	24.158
pupil ∗ cardiac phase ∗ race ∗ object	0.006	0.994	2.411e-11	1.000	4.003e-9
Weapons Identification Task – accuracy					
pupil	0.886	0.114	1.000	2.904e-5	4420.106
cardiac phase ∗ race ∗ object	0.120	0.880	1.000	1.988e-7	3.698e+7
pupil ∗ cardiac phase ∗ race ∗ object	0.006	0.994	1.727e-10	1.000	2.867e-8

Note: pupil = pupil condition; cardiac phase = diastole or systole; condition = fearful or neutral; race = Black or White; object = tool or weapon. P(incl) and P(excl) are the prior inclusion and exclusion probabilities, respectively. P(incl | data) and P(excl | data) are the posterior inclusion and exclusion probabilities, respectively. These represent the probability that a predictor is included or excluded in the model before and after considering the data. They are determined by summing prior or posterior model probabilities of all models containing or excluding that predictor. BF_{incl} is the inclusion Bayes factor which measures the shift from prior inclusion odds to posterior inclusion odds and can be interpreted as the evidence in the data for including a predictor.

In the WIT, there were effects of pupil condition on both response times (BF=1.9x10^{13}; Fig1G–H; Table 1A) and accuracy (BF=4420; Fig1I–J; Table 1A), with larger pupils resulting in faster response times and lower accuracy. Here again, pupil condition did not interact with race (Black versus White prime; response time BF=0.017, accuracy BF=0.019), object (tool versus weapon; response time BF=0.028, accuracy BF=0.034) or cardiac phase (diastole versus systole; response time BF=0.010, accuracy BF=0.018). Previous findings of race-driven object misidentification during cardiac systole (Azevedo et al., 2017) were replicated (accuracy BF=3.7x10^{7}; Table 1A, Fig 2A). Similarly, there was evidence of a three-way interaction between race, object identification, and cardiac phase on the effect of response times (BF=24.16; Table 1A, Fig 2B). However, neither of these was influenced by pupil condition (accuracy BF=2.9x10^{-8}, response time BF=4.0x10^{-9}; Table 1A). Post hoc tests for differences between pupil conditions revealed that response times were faster for larger pupils (NB versus SB BF=2.153x10^{10}, NM versus MM BF=9.681x10^{11}; Table 1B) and less accurate (NB versus SB BF=2257.78, NM versus MM BF=15.76; Table 1B). Response times were also faster in the shaded binocular (SB) condition compared to the normal monocular (NM) condition (BF=107235; Table 1B). Although this difference was not found for accuracy (BF=0.737, Table 1B), the same pattern of results was observed (Fig1J). This was supported by a significant positive correlation between reaction times and accuracy across runs and individuals (Pearson's ρ=0.525, 95% CI [0.471, 0.574], BF=3.152x10^{51}).

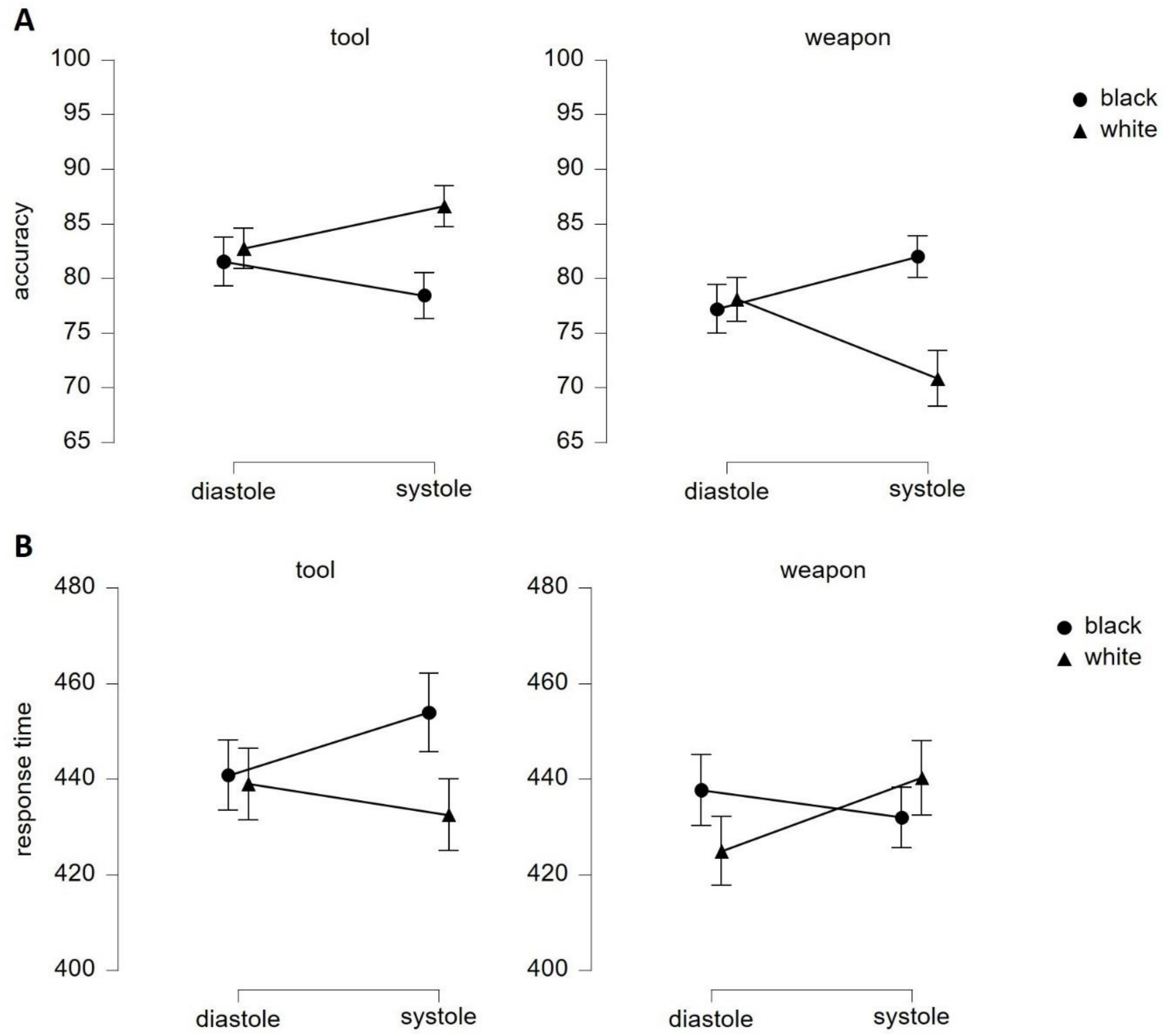

Figure 2. Replicated finding of race-driven object misidentification at cardiac systole
(A) Left: Accuracy was lower when identifying tools after Black compared to White faces during systole. Right: Accuracy was lower when identifying weapons after White compared to Black faces during systole. (B) Left: Response time was longer when identifying tools after Black compared to White faces during systole. Right: Response time was longer when identifying weapons after White compared to Black faces during systole. Values are means with 95% confidence intervals.

Table 1B. Post Hoc Comparisons – pupil conditions

Response time

		Prior Odds	Posterior Odds	$BF_{10,U}$	error %
NB	SB	0.414	8.916e+9	2.153e+10	1.970e-17
	NM	0.414	17.156	41.417	6.831e-4
	MM	0.414	4.066e+15	9.815e+15	1.302e-18
SB	NM	0.414	44418.194	107235.008	1.478e-11

	MM	0.414	55.577	134.175	2.229e-4
NM	MM	0.414	4.010e+11	9.681e+11	3.376e-14

Accuracy

		Prior Odds	Posterior Odds	$BF_{10,\,U}$	error %
NB	SB	0.414	935.203	2257.779	8.480e-10
	NM	0.414	0.672	1.621	0.015
	MM	0.414	13726.440	33138.558	4.850e-11
SB	NM	0.414	0.305	0.737	0.030
	MM	0.414	0.101	0.244	0.084
NM	MM	0.414	6.529	15.763	0.002

Note: Posterior odds have been corrected for multiple comparisons by setting the prior probability that the null hypothesis holds across all comparisons to 0.5. Bayes factors shown are uncorrected. NB = Normal Binocular; SB = Shaded Binocular; NM = Normal Monocular; MM = Mydriatic Monocular.

CONCLUSIONS

Our study revealed that pupil size does not influence emotional processing or the expression of stereotypical racial bias in the emotional intensity judgement task or the weapons identification task. This lack of an effect of pupil dilation contrasts with the observed effects of the cardiac cycle, which captures the visceral afferent information about autonomically mediated states of cardiovascular arousal, on emotional judgements and racial bias. Pupillary conditions did show effects in the weapons identification task that were limited to response time and accuracy: larger pupils resulted in faster response times and lower accuracy (i.e. shaded versus normal binocular vision and mydriatic versus normal monocular vision). In addition, trends in the data suggested that monocular, dominant-eye vision allows for slower response times and better accuracy than shaded binocular vision. Thus, dominant monocular vision may outperform shaded binocular vision in certain contexts. These effects, in the absence of direct influences on fear and threat processing, are likely attributable to a passive change in visual acuity. We cannot however exclude the possibility that external manipulation of pupil size may actively decouple pupillary interaction with emotional state and impact state-dependent recruitment of rods and cones (Franke et al., 2022), impeding decision-making (de Gee et al., 2014) and behavioural performance. Our data nevertheless advocate for greater consideration of appropriate eyewear, particularly for those in occupations involving split-second decisions such as police officers.

To our knowledge, this is the first study examining how externally manipulated pupil dilation influences performance on emotional tasks. Prior work concentrates on pupil size as an inert index of psychophysiological arousal (Rigato et al., 2016; van Kempen et al., 2019). Larger pupil size at baseline is associated with slower responses, while reactive increases in pupil size to the presentation of target stimuli correlates with faster response times (van Kempen et al., 2019). Future studies should examine differences between externally versus internally generated pupil responses as they relate to arousal pathways. Moreover, associated eye-widening may be an important consideration, both in terms of stimulus and participant, as it has been shown to enhance emotional processing in both the expresser and observer (Lee et al., 2013).

Autonomically mediated states of cardiovascular arousal influence perception via baroreceptor firing at systole. These signals enhance the detection and processing of threat (Garfinkel et al., 2021; Garfinkel et al., 2014) and amplify the expression of threat-related racial bias (Azevedo et al., 2017). Dynamic pupillary changes are coupled to social and emotional behaviours (Harrison et al., 2006) and an interoceptive neural representation of one's own pupil size likely contributes to the guidance of social inferences (Harrison et al., 2009; Kret & De Dreu, 2019; Prochazkova et al., 2018). We therefore predicted that pupil size would influence both the perception of fear from facial cues and the behavioural expression of implicit racial biases (potentially linked to fear of 'outgroups'), either through the prioritized processing of salient low spatial frequency visual information or through engagement of the same central interoceptive processes (potentially monoaminergic), supporting cardiovascular influences on affective behaviour. Our findings suggest a differential lack of impact of pupil dilation relative to the reliable effect of dynamic cardiac signalling on affective processing. Importantly, the null effect of pupil size may be attributable to the small sample size and lack of statistical power in this study. It is possible that the effect of pupil size may be small and therefore difficult to observe in a study of this scale. Future studies should consider greater numbers of observations to improve sensitivity in determining the effect of pupil size on affective processing. Still, observations from the present study are relevant to understanding behavioural changes under arousal and threat and may help guide interventions to avoid unwanted consequences of erroneous and biased decisions 'in the field' under high-stress situations. This study sets the scene for further work to understand the different contributions of organ-specific autonomic responses to adaptive behaviour.

DATA & SOFTWARE AVAILABILITY

Fully anonymized data are available upon request.

CONSENT

Eligibility was assessed prior to entrance into the study via email. Key safety concerns were discussed before invitation. Participants were also informed that they could contact the researchers with any concerns and withdraw at any time. Written consent was taken before commencing the tasks and participants were given all relevant information regarding task logistics and data use.

AUTHOR CONTRIBUTIONS

HC, YN, and SG contributed to the design of the study. Stimuli were provided by RA and MT. JW and RK recruited participants, collected data, and wrote initial drafts of the manuscript. SS analysed data, produced figures, and prepared the final version of the manuscript along with HC. SS, HC, RA, MT, YN, and RK contributed to the final version of the manuscript.

COMPETING INTERESTS

The authors report no competing interests.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The authors did not use generative AI technologies for preparation of this work.

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