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Reward elicits cognitive control over emotional distraction: Evidence from pupillometry

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Abstract

Attention is biased toward emotional stimuli, even when they are irrelevant to current goals. Motivation, elicited by performance-contingent reward, reduces behavioural emotional distraction. In emotionally neutral contexts, reward is thought to encourage use of a proactive cognitive control strategy, altering anticipatory attentional settings to more effectively suppress distractors. The current preregistered study investigates whether a similar proactive shift occurs even when distractors are highly arousing emotional images. We monitored pupil area, an online measure of both cognitive and emotional processing, to examine how reward influences the time course of control. Participants (n = 110) identified a target letter flanking an irrelevant central image. Images were meaningless scrambles on 75% of trials; on the remaining 25%, they were intact positive (erotic), negative (mutilation), or neutral images. Half the participants received financial rewards for fast and accurate performance, while the other half received no performance-contingent reward. Emotional distraction was greater than neutral distraction, and both were attenuated by reward. Consistent with behavioural findings, pupil dilation was greater following emotional than neutral distractors, and dilation to intact distractors (regardless of valence) was decreased by reward. Although reward did not enhance tonic pupil dilation (an index of sustained proactive control), exploratory analyses showed that reward altered the time course of control—eliciting a sharp, rapid, increase in dilation immediately preceding stimulus onset (reflecting dynamic use of anticipatory control), that extended until well after stimulus offset. These findings suggest that reward alters the time course of control by encouraging proactive preparation to rapidly disengage from emotional distractors.

Keywords Emotion · Motivation · Distraction · Cognitive control · Reward · Pupillometry

Emotional distractions can be difficult to ignore (Pourtois, Schettino, & Vuilleumier, 2013; Okon-Singer, Tzelgov, & Henik, 2007; Yiend, 2010). Although attentional biases to emotional stimuli are often thought of as reflexive (e.g., Brosch, Pourtois, Sander, & Vuilleumier, 2011), increasing task motivation via performance-contingent reward can enhance cognitive control of emotional distractions (Padmala & Pessoa, 2014; Padmala, Sirbu, & Pessoa, 2017; Walsh, Carmel, Harper, & Grimshaw, 2018), just as motivation enhances control in emotionally neutral contexts (Chiew & Braver, 2013, 2014; Locke & Braver, 2008; Padmala & Pessoa, 2011). However, we know little about the cognitive mechanisms by which motivation enhances control of emotional distractions. The current study uses pupillometry, a temporally sensitive measure of both cognitive control and emotional processing (Beatty & Lucero-Wagoner, 2000; Bradley, Miccoli, Escrig, & Lang, 2008; Laeng, Sirois, & Gredebäck, 2012), to address the question of how reward influences the time course of control when distractors are emotional.

The dual mechanisms of control framework (DMC; Braver, 2012; Braver, Gray, & Burgess, 2007), which is usually applied in emotionally neutral contexts, provides predictions as to how motivation might influence the control of emotional distractions. Cognitive control allows us to focus on task-relevant information while ignoring task-irrelevant

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distractions. Often, we control distraction using a reactive control strategy, disengaging from distractors after they capture our attention (Geng, 2014). Proactive control requires greater effort, because it involves anticipatorily preparing to suppress distractors before they appear. Neurally, proactive control recruits the lateral prefrontal cortex (PFC) to actively maintain representations of goals prior to stimulus onset (Braver, 2012; Braver, Paxton, Locke, & Barch, 2009). This activation can be sustained over time, or dynamically implemented before stimulus onset. Reactive control also recruits lateral PFC, but does so after a distractor has appeared (Braver, 2012; Braver et al., 2009). The terms *reactive* and *proactive* here refer to the timing of the implementation of control, and not to specific mechanisms per se. Proactive mechanisms could include, for example, anticipatory enhancement of target representations, or suppression of distractor location or features; reactive mechanisms could include facilitation of conflict detection, or a speeding of disengagement.

A central tenet of the DMC framework is that we shift to more effective, but more effortful, proactive control only when it is worthwhile to do so (see Botvinick & Braver, 2015, for a review). Reward is one incentive that is known to motivate a shift to proactive control in emotionally neutral contexts (Chiew & Braver, 2013, 2014; Fröber & Dreisbach, 2014, 2016; Hefer & Dreisbach, 2016; Locke & Braver, 2008; Padmala & Pessoa, 2011; Yamaguchi & Nishimura, 2018). This proactive shift is thought to be implemented via connections between reward-processing areas (such as the ventral striatum and orbitofrontal cortex) and cognitive control regions (such as the anterior cingulate cortex and dorsolateral prefrontal cortex; Botvinick & Braver, 2015; Pessoa, 2009; Pessoa & Engelmann, 2010). However, it is not known whether motivation similarly enhances control of emotional distraction via a shift to proactive control.

It is reasonable to think that reward might enhance control of emotional distractions via different mechanisms than it does for neutral distractions. Attention is biased toward biologically relevant emotional stimuli because they are important for survival and reproduction (LeDoux, 2012). Therefore, it might be adaptive for them to always capture our attention, regardless of their relevance to current goals, so that we can determine whether they require immediate action before we disengage from them. Emotional distractors (unlike their neutral counterparts) are thought to bias our attention via both exogenous (reflexive) and endogenous (goal-driven) processes (Brosch et al., 2011; Mohanty & Sussman, 2013; Mulckhuyse, 2018; Sussman, Jin, & Mohanty, 2016), making them more difficult to ignore (Okon-Singer et al., 2007; Pourtois et al., 2013; Yiend, 2010). If emotional distractors bias our attention reflexively, we may not be able to control them proactively. Instead, we may be more likely to control emotional distraction by up-regulating reactive control so that we can rapidly disengage from distractors. Our primary research question is therefore whether the availability of rewards encourages proactive control, just as it does in emotionally neutral contexts.

Recent neuroimaging studies provide some support for the proactive control of emotional distraction under reward. In a series of studies Padmala and colleagues (Padmala & Pessoa, 2014; Padmala et al., 2017) had participants ignore a centrally presented distractor image while judging the orientation of two flanking lines. Participants were slower when negative compared to neutral distractors were presented (i.e., they showed an emotional distraction effect). On some trials, a pretrial reward cue appeared, indicating availability of monetary reward for fast and accurate performance on the upcoming trial. Reward sped up responses, and also eliminated emotional distraction. Functional magnetic resonance imaging (fMRI) showed that participants with greater ventral striatum activation during the reward cue phase showed a greater benefit from reward on a behavioural measure of emotional distraction (Padmala et al., 2017). Furthermore, there was stronger functional connectivity between the ventral striatum and frontal and parietal regions involved in attentional control while processing reward compared with nonreward cues, consistent with the recruitment of proactive control mechanism to reduce emotional distraction when rewards were signalled.

Although neuroimaging findings support the hypothesis that reward encourages the implementation of proactive control, dynamic changes in control are best examined using more temporally sensitive measures of cognitive and emotional processing. The current preregistered study uses pupillometry (a high-resolution measure of changes in pupil area over time) to examine the effect of reward on the time course of cognitive control of emotional and neutral distractions. Pupil dilation marks changes not only in perceived luminance (Mathôt & Van der Stigchel, 2015), but also in cognitive processing; dilation is an established, temporally sensitive measure of cognitive control (Beatty & Lucero-Wagoner, 2000; Chatham, Frank, & Munakata, 2009; Chevalier, Martis, Curran, & Munakata, 2015; Chiew & Braver, 2013, 2014; Jones, Siegle, & Mandell, 2015; Kahneman, 1973; Rondeel, van Steenbergen, Holland, & van Knippenberg, 2015). Pupil dilation is driven by release of the neuromodulator norepinephrine (NE) from the locus coeruleus (LC; Joshi, Li, Kalwani, & Gold, 2016; Laeng et al., 2012; Rajkowski, Majczynski, Clayton, & Aston-Jones, 2004). The LC (located in the rostral pons) provides the major source of NE to the brain, sending dense projections to diverse brain regions, including those involved in attentional control (e.g., PFC, parietal cortex, superior colliculus, the pulvinar nucleus) and reward processing (including VTA, eliciting dopaminergic release from the nucleus accumbens; see Laeng et al., 2012; Sara, 2009, for reviews). It is thought that NE has an important arousal-inducing function, which promotes cognitive performance

(Laeng et al., 2012; Samuels & Szabadi, 2008; Sara, 2009). Furthermore, NE is thought to facilitate changes to attention, cognition, and behaviour by enhancing functional connectivity between various brain regions (Coull, Büchel, Friston, & Frith, 1999; Sara, 2009). Pupillometry is sensitive to both emotional arousal (e.g., Bradley et al., 2008) and cognitive effort (see Kahneman, 1973; Laeng et al., 2012), and so is well-suited to our aims.

Two measures of pupil dilation are relevant: Tonic dilation refers to changes in baseline pupil area (often measured during an intertrial-interval period; e.g., Chiew & Braver, 2013, 2014; Heitz, Schrock, Payne, & Engle, 2008), and reflects state-related changes such as increases in sustained arousal; phasic dilation is an event-related transient change triggered by a specific stimulus or event (baselined to a preceding time period). Recently, Chiew and Braver (2013, 2014) used both tonic and phasic pupil dilation to measure the time course of motivationally induced enhancements of cognitive control. Participants were rewarded for successful performance on a cognitive control task (AX continuous performance), which elicited behavioural performance consistent with a shift toward proactive control. Reward increased tonic pupil dilation, thought to reflect increases in arousal that accompany a shift to a sustained proactive control strategy. Reward also increased preparatory phasic pupil dilation (triggered by the cue for an impending target), thought to reflect a more dynamic form of proactive control (Chatham et al., 2009; Chevalier et al., 2015). These findings suggest that both tonic and phasic changes in pupil dilation can mark a motivationally driven shift to proactive control, at least in an emotionally neutral context.

Pupil dilation also indexes emotional arousal induced by viewing emotional images (Bradley et al., 2008; Cohen, Moyal, & Henik, 2015; Henderson, Bradley, & Lang, 2014; Kinner et al., 2017; Snowden et al., 2016; Vanderhasselt, Remue, Ng, & De Raedt, 2014), and correlates with measures of skin conductance (Bradley et al., 2008). This emotional pupil response is subject to top-down influences. When cognitive control is enhanced via conflict manipulations (flanker incongruence; Cohen et al., 2015), or by implementation of effective emotion-regulation strategies (Kinner et al., 2017; Vanderhasselt, et al., 2014), pupil dilation in response to negative emotional images is reduced. Furthermore, pupil dilation during anticipation of a negative emotional image is inversely related to pupil dilation in response to the image itself (Vanderhasselt et al., 2014). Therefore, increased anticipatory pupil dilation can index proactive control of emotional processing, and reduced poststimulus pupil dilation can index attenuated processing of emotional content.

The current study takes advantage of the pupil's sensitivity to the timing of cognitive effort and emotional processing, to determine whether reward reduces emotional distraction via a shift to proactive control. Participants identified a target letter flanking an irrelevant central image. The behavioural task is a replication of that used by Walsh et al. (2018) to show that reward attenuates distraction by both positive and negative distractors. Images were meaningless scrambles on 75% of trials, a proportion that gives rise to a predominantly reactive control strategy (Bugg & Crump, 2012; Grimshaw, Kranz, Carmel, Moody, & Devue, 2018); on the remaining 25% of trials, however, intact positive (erotic couples), negative (mutilations), or neutral images (of people) were presented. Distractor valence was blocked, so that participants could anticipate the type of distractor they might see, but not on which trial an intact distractor would occur. Half the participants received performance-contingent financial rewards for fast and accurate performance, while the other half received a fixed payment that was not linked to performance.

We expected that the motivational manipulation would enhance control, reflected by reduced behavioural emotional distraction (replicating Walsh et al., 2018), and a reduction in the pupil's response to emotional distractors. Our key question was whether reward improves performance by encouraging people to shift to a proactive control strategy to ignore emotional distractors. If reward elicits proactive control via a global strategy that is maintained across an experimental block, we expect reward to increase tonic pupil dilation. If reward elicits proactive control via a dynamic strategy that occurs on a trial-by-trial basis, we expect reward to enhance phasic, prestimulus pupil dilation. Additionally, we examined phasic pupil dilation in the poststimulus period, to provide insight on the consequences of control for subsequent processing of distractors. Specifically, we predicted that reward would reduce the dilation to intact (relative to scrambled) distractors, reflecting reduced distractor processing. Lastly, we examined Reward × Valence interactions in all planned analyses, to determine whether reward influences the time course of control (indexed by pupil dilation) of neutral, negative, and positive distractions similarly.

Method

This study was preregistered on Open Science Framework (OSF) prior to data collection (osf.io/jd96p/). The preregistration adheres to the disclosure requirements of OSF. All data, materials, and code used for image manipulation and statistical analyses, are available at osf.io/yhkdr.

Sample size determination

To determine the sample size needed to test the effect of reward on the pupil's response to emotional images, we assumed that the effect of reward on poststimulus pupil dilation would be comparable in size to the effect of reward on a behavioural measure of emotional distraction (RT), which was d_s = .519 in Walsh et al. (2018). This effect size is similar to that reported by Cohen et al.

(2015; d_s = .503) for the effect of flanker congruency on pupillary response to negative (relative to neutral) images. A sample size analysis in G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) indicated 47 participants per group would provide sufficient power to detect a similar effect of reward on emotional distraction 80% of the time (alpha = .05). Rounding up to accommodate counterbalancing yielded a sample size of 54 participants per reward condition. A sensitivity analysis (also in G*Power, with alpha = .05) showed that 54 participants per group provide sensitivity to detect an effect of d_s = .482 or larger at 80% power.

Participants

A total of 114 participants were recruited from the community in Wellington, New Zealand, via fliers and emails. Participants reported normal vision, spoke fluent English, and were not currently being treated for depression or anxiety. Participants were randomly allocated to the control or reward groups. Four participants did not complete the task due to technical errors (experiment crashing n = 3, eye-tracker technical issues n = 1). Replacement participants were run to reach the sample size goal, resulting in 55 participants in each group (control group: 13 men, 42 women; reward group: 18 men, 37 women; between 18 and 39 years old, M = 23, SD = 4). We exceeded the target of 54 participants per condition because a participant who was mistakenly excluded and rerun did not actually meet the preregistered exclusion criteria; an additional participant was therefore recruited to balance the size of the control and reward groups. The study was approved by the School of Psychology Human Ethics Committee, by delegated authority of the Victoria University of Wellington Human Ethics Committee. Participants provided informed consent prior to participation.

Stimuli and materials

The experiment was run on an Acer PC with a 22-in. flat-screen monitor with 1024 × 768 pixel resolution and a 120-Hz refresh rate. Viewing distance was maintained by a chin rest 60 cm from the screen. The experiment was programmed and run on E-Prime 2.0 (Psychology Software Tools, 2012). A nine-point calibration and validation of the eye tracker was performed at the beginning of the session. Between each block, a manual drift check was performed, and if necessary the calibration and validation were performed again. Area of the left pupil (in arbitrary units) was recorded using an Eyelink 1000-plus desktop mounted eye-tracker (SR Research Ltd., Mississauga, ON) using a 1000-Hz sampling rate.

The images were selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008) and comprised 12 high-arousal negative images (gory images of mutilations), 12 high-arousal positive images (erotic images of heterosexual couples), and 12 neutral images (of people). So that the positive and negative image sets could be matched on arousal, separate but overlapping image sets were selected for men and women. See the Supplementary Materials for the valence and arousal ratings for the image sets (Table S1) and specific IAPS images used and the mean ratings for the image sets (Table S2).

Three scrambled versions of each image were used as control stimuli (see an example in Fig. 1). The scrambled images were created in MATLAB by performing a 2D fast Fourier transform, followed by phase randomisation, and reconstruction of the image. The process of phase scrambling also matched the images on average RMS contrast. The scrambled images maintain the same lower level visual properties (i.e., colour, amplitude spectrum) as the original image while changing the position of the spatial frequency components and removing meaningful content. All images (intact and scrambled) were matched on average luminance using the SHINE MATLAB toolbox (Willenbockel et al., 2010).

The target display (see Fig. 1a) consisted of a centrally presented image (11° width × 8.26° height) on a grey background, with six white letters (0.86° × 0.92°) placed 0.75° above and three 0.75° below the image's horizontal edge. In the centre of the image was a light grey cross which provided a focal point for participants to help them control eye movements. The image was an intact IAPS image on 25% of trials, and a scrambled image on 75% of trials. On each trial, five of the letters were *O*s and the target was a *K* or *N*. The target letter appeared in each location an equal number of times. The display was similar to that used in Gupta, Hur, and Lavie, (2016) and Walsh et al. (2018).

Task and procedure

Participants were tested in a dimly lit room. Participants were told that the images were irrelevant to their task, so they should ignore them. They were asked to avoid blinking excessively, to keep their head still, and to continue looking at the centre of the screen throughout a trial.

For all participants (in both reward and control conditions), each trial (see Fig. 1b) began with a large, bold, white fixation cross on a grey background. When they were ready to start the trial, the participant looked directly at the bold cross for 1,000 ms, at which point it turned into a smaller white fixation cross, indicating the start of the trial. The smaller fixation cross was presented for a constant duration of 2,000 ms and was followed by the target display for 200 ms. Participants indicated (as quickly and accurately as possible) whether the target letter was a *K* or an *N*, using the keys 1 and 2 on the number pad, with the index and middle fingers of their right hand. Following the target display, the fixation cross reappeared for 1,800 ms (a fixed response window, regardless of when a response was made). Feedback was then displayed for 100 ms, indicating whether the participant was *correct* or *incorrect* in white font. If no response was made

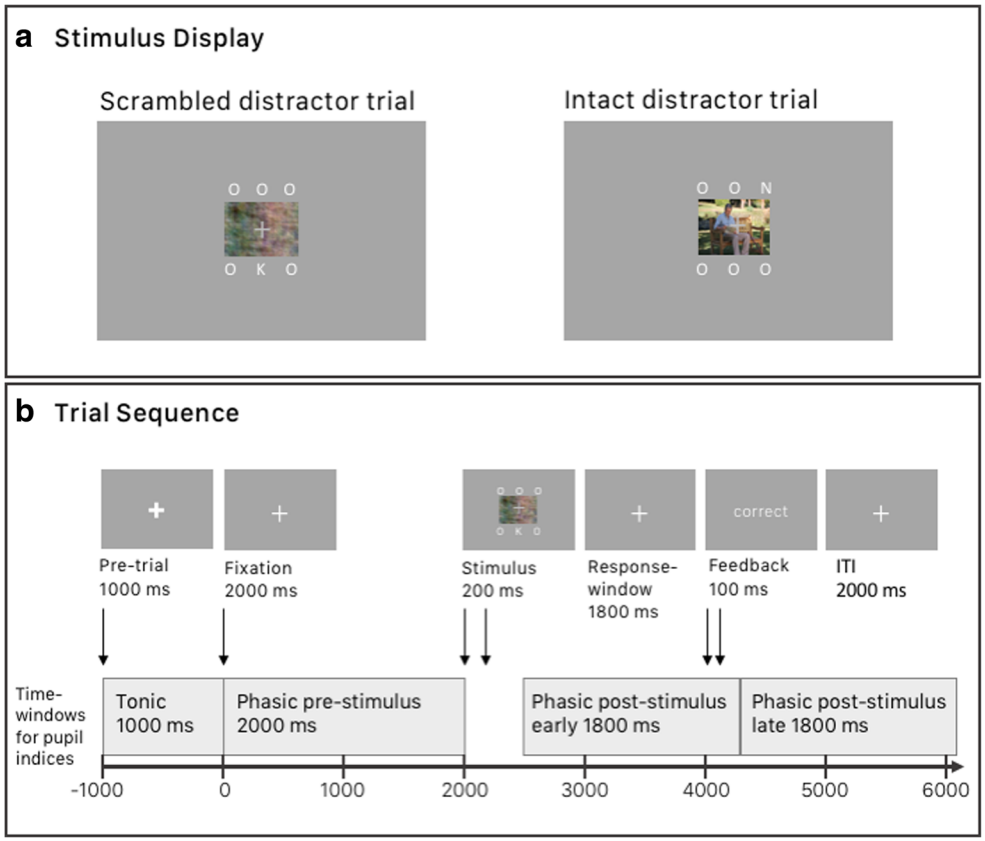

Fig. 1 Target display (**a**) and trial sequence (**b**). **a** Example of a scrambled (left) and intact (right) target display. **b** Trial sequence. Arrows indicate onset of a display. Preregistered time windows for pupil analyses are represented by grey shaded boxes. For illustrative purposes, images are not to scale; the central part of the display is enlarged

within the response window then the feedback stated *please respond faster*. Following the feedback, the smaller fixation cross appeared again throughout the 2,000 ms intertrial interval (ITI). At the end of a trial, the larger bold fixation cross again appeared, and the next trial began when the participant had fixated on it for 1,000 ms.

The experiment began with a set of 12 practice trials, arranged in three miniblocks (negative, neutral, positive) of four trials each, with one intact and three scrambled images appearing randomly in each miniblock. The images presented in the practice trials were different from those used in experimental blocks. Following the practice trials was a baseline block of 24 trials. The purpose of the baseline block was to calculate participants' individual median RT, to be used as a threshold for reward during the experimental blocks and to provide a baseline from which to measure tonic pupil dilation in subsequent blocks. The baseline block consisted of 24 scrambled distractor trials. The phase-scrambled images used in the baseline block were derived from a set of 12 neutral images (different from those used in the neutral experimental block) and were presented once each. Following the baseline block, participants completed six experimental blocks of 48 trials each. Each block comprised 12 different intact and 36 scrambled image trials (in random order), all with one valence. There were two sequential blocks of each valence (e.g., positive, positive, negative, negative, neutral, neutral), resulting in each intact and scrambled image being presented twice in total. Valence order was counterbalanced across participants.

The Behavioural Activation and Inhibition Scale (Carver & White, 1994) was administered to participants at the end of the experimental session; however, due to a technical error, the responses were not recorded and were therefore not analysed.

Reward manipulation

Following the baseline block, the reward group was informed of the potential to earn points and move up levels in the following six blocks of trials. They were told that winning points would lead to achieving 'levels', and that each new level increased total earnings upon task completion by $2.50. Participants began on level one ($10). Level 2 required 53 points ($12.50); 53 additional points were needed to ascend to each new level, up to Level 6 ($20). All participants actually earned $20 in supermarket vouchers at the end of the study, regardless of the amount they presumed they had won during the study. Feedback was provided after every trial: If participants responded accurately and faster than their median response time in the baseline block, then they earned 1 point,

and saw: 'you won a point!'; if they were accurate but slower than the reward threshold, then they saw 'correct', and if they were incorrect they saw 'incorrect'. Feedback on overall performance was provided in each break between blocks. If a participant moved up a level in the preceding block, then the feedback screen read, 'Well done! You have moved up a level.' If not, it read 'No level up'. On the same screen, they saw their current point total, current level, and mean proportion correct for the previous block. Participants were reminded at this point to be fast and accurate. To minimise the potential for a speed–accuracy trade-off due to the reward RT deadline, a warning to keep trying to be accurate was provided during the breaks between blocks if accuracy fell below 95% across the previous block.

The control group performed the task with no performance-contingent motivational incentive. They received informative feedback after each trial (*correct*, *incorrect*, or *please respond faster*). They did not have the opportunity to earn points and did not receive overall performance feedback between blocks. Instead they saw a screen saying, 'please take a short break'.

Preregistered analyses

The following descriptions of data processing, calculation of indices, inference and exclusion criteria, and analyses were all preregistered.

Pupillometry data processing Pupillometry data were preprocessed in MATLAB using a combination of open source code (see acknowledgements), and our own code. Blinks <500-ms long were linearly interpolated. Partial blinks were identified by extreme (unrealistic) changes in pupil area from one time point to the next; pupil area during these partial blinks was then linearly interpolated. Pupil indices were calculated using mean pupil area (in arbitrary units) across several time windows (as outlined in more detail below). Pupil indices were calculated using mean pupil area (in arbitrary units) across several time windows. Baseline subtraction was used to calculate indices, as it is more robust to baseline artefacts, and increases statistical power, relative to divisive baseline corrections (Mathôt, Fabius, Van Heusden, & Van der Stigchel, 2017). Only trials with correct responses were included in phasic pupil indices.

The first two time windows (tonic and phasic prestimulus; see Fig. 1b) provide indices to test predictions regarding the effects of reward on anticipatory, proactive control. The first window provides an index of *tonic* proactive control: mean pupil area across the 1,000-ms time window prior to trial onset, baselined to the grand mean of pupil area across the 200-ms time window immediately preceding trial onset across all 24 (nonreward, scrambled image only) baseline block trials. The second window provides an index of *phasic* proactive control: mean pupil area across the 2,000-ms time window starting from fixation onset, and ending at stimulus onset, baselined to mean pupil area across the 200-ms time window immediately preceding fixation onset. This phasic proactive control index reflects dynamic, effortful preparation immediately preceding stimulus onset.

Two phasic poststimulus (early and late) indices were created to test predictions regarding how reward affects the pupil's response to the emotional distractors. The early poststimulus window begins 500 ms poststimulus onset and extends for 1,800 ms.[1] The late poststimulus window begins immediately following the first and extends for 1,800 ms until the end of the trial. For both the early and late poststimulus indices, the baseline is the mean pupil area 200 ms immediately preceding stimulus onset. These poststimulus phasic indices for intact image trials are subtracted from the phasic indices on scrambled image trials (thus controlling for pupil dilation in response to low-level visual properties) to obtain an index of the pupil's response to the content of the intact images. All indices were calculated for each individual participant, separately for each valence.

Data exclusion criteria Trials were excluded if they were missing more than 50% of pupil samples, Additionally, trials were excluded from specific analyses if the baseline period for that time window was missing more than 50% of its pupil area samples. A mean of 13 (out of 288) indices were removed per participant (min = 0, max = 66; see OSF materials for more information on the breakdown of trial exclusions). Our preregistration stated that participants would be excluded if they had less than 75% accuracy overall, less than 60% accuracy on a given block, loss of more than 20% of their pupil samples overall, or had fewer than 10 trials in a given condition. No participants met these exclusion criteria.

Inference criteria P values < .05 were accepted as statistically significant, and relevant follow-up analyses were conducted on these effects. One-tailed or two-tailed tests for planned comparisons were specified in the predictions and were not corrected for multiple comparisons (see Armstrong, 2014). Exploratory analyses were not corrected for multiple comparisons (except for the pupil–behaviour correlations), but are noted as exploratory and should be interpreted with caution. Note that distractor type (intact, scrambled) is not a factor in the analyses because it is either irrelevant (for the proactive indices) or included in the transformations (for the poststimulus indices). Cohen's d effect sizes are d_z for within-subjects comparisons, and d_s for between-subjects comparisons.

[1] Other (unpublished) studies from our lab, in which participants passively viewed these same images, typically find that effects of distractor type (intact vs. scrambled) and valence did not begin to emerge until 500 ms poststimulus onset.

Results

All analyses were preregistered unless noted as exploratory. All preregistered predictions are confirmed as supported, or not supported. Significant findings that were not predicted are noted as such. Data and code to reproduce analyses and figures are provided on OSF (osf.io/yhkdr).

Behavioural distraction

Mean response times (RTs) and proportion correct scores are included in Table 1. Trials with no response or with anticipatory responses (RT < 200 ms) were counted as errors. Examination of means suggests that (as predicted) reward elicits a speed–accuracy trade-off, speeding up responses at a small cost to accuracy. This speed–accuracy trade-off is examined in supplementary analyses (in which preregistered ANOVAs are performed on correct RTs and proportion correct, and an exploratory ANOVA is conducted on inverse-efficiency scores; Bruyer & Brysbaert, 2011), in which we show that it does not account for the effect of reward group on emotional distraction. Therefore, we followed our preregistered plan and focused our analyses on distraction indices, which were calculated as ((mean RT intact − mean RT scrambled) / mean RT scrambled)) × 100 (see Fig. 2). These distraction indices reflect percentage slowing due to intact distractors, relative to performance on scrambled trials. A simple difference score between intact and scrambled RTs was not used because of the overall difference in RTs between the reward and control groups. However, for ease of interpretation, we present the difference scores in milliseconds (intact − scrambled) in Table 1.

A mixed-model ANOVA was conducted on distraction indices with distractor valence (negative, neutral, positive) as a within-subjects factor and reward group (control, reward) as a between-subjects factor. Neutral valence was entered as the middle level in the ANOVA so that effects of emotional versus neutral distraction could be examined as quadratic effects of valence (as was done in Grimshaw et al., 2018). As predicted, overall, emotional images were more distracting than neutral images, shown by the quadratic main effect of valence: $F(1, 108) = 99.24$, $p < .001$, $\eta_p^2 = 0.479$. Planned comparisons showed that distraction from positive ($M = 16.30\%$, $SD = 11.82\%$) and negative ($M = 15.57\%$, $SD = 12.51\%$) images did not differ from each other ($p = .474$, two-tailed) and so positive and negative distraction were collapsed together into emotional distraction ($M = 15.93\%$, $SD = 10.92\%$), which was greater than neutral distraction ($M = 6.88\%$, SD 6.19%), $t(109) = 9.04$, $p < .001$, $d = 0.862$, 95% CI [7.07, inf] (one-tailed).

Crucially, as predicted, the reward group was less distracted overall than the control group: $F(1, 108) = 38.10$, $p < .001$, $\eta_p^2 = 0.261$ (controls: $M = 17.10\%$, $SD = 7.85\%$; reward: $M = 8.73\%$, $SD = 6.28\%$). Also as predicted, reward reduced emotional distraction to a greater degree than it did for neutral distraction, reflected by the quadratic Reward × Valence interaction, $F(1, 108) = 24.366$, $p < .001$, $\eta_p^2 = 0.184$. There was no difference between positive and negative distraction in either the control or reward groups (both ps > .473, two-tailed), so positive and negative distraction were collapsed together for the following planned one-tailed tests. Emotional distraction was significantly reduced in the reward group ($M = 10.25\%$, $SD = 7.82\%$) compared to the control group ($M = 21.61\%$, $SD = 12.35\%$), $t(108) = 6.37$, $p < .001$, $d = 1.214$, 95% CI [8.40, inf] (one-tailed). Neutral distraction was also significantly reduced in the reward group ($M = 5.68\%$, $SD = 5.62\%$) compared to the control group ($M = 8.08\%$, $SD = 6.55\%$), $t(108) = 2.06$, $p = .021$, $d = 0.392$, 95% CI [0.46, inf] (one-tailed), though to a lesser extent than emotional distraction was.

Pupil data

Pupil area across the entire trial (baselined against the mean of the 200-ms pretrial period) is shown separately for the control and reward groups in Fig. 3.

Proactive control pupil indices See Table 2 for means and standard deviations for phasic and tonic proactive control indices. Note that the tonic means are all negative values; this is because tonic pupil area decreased across the experimental session in both groups, relative to the preexperimental baseline block at the start of the session. This is not unusual in long experimental sessions. For simplicity, we will refer to differences in dilation between experimental conditions; however, these should be interpreted in light of an overall pattern of constriction in experimental relative to baseline blocks.

Separate mixed-model ANOVAs were conducted on the tonic and phasic proactive control indices, each with valence (negative, neutral, positive) as a within-subjects factor and reward group (reward, controls) as a between-subjects factor. Analysis of the tonic proactive indices (reflecting sustained dilation across blocks; see Fig. 4) revealed that, as predicted, there was higher tonic dilation in emotional compared with neutral blocks, as reflected in the quadratic main effect of valence, $F(1, 108) = 9.03$, $p = .003$, $\eta_p^2 = 0.077$. Planned comparisons showed that tonic pupil dilation in positive ($M = -66$, $SD = 209$) and negative ($M = -82$, $SD = 227$) blocks did not differ from each other, $t(109) = 1.48$, $p = .141$, $d = 0.141$, 95% CI [−37, 5] (two-tailed), and so positive and negative tonic dilation were collapsed together into emotional tonic dilation. Tonic dilation was greater on emotional ($M = -74$, $SD = 210$) than on neutral blocks ($M = -105$, $SD = 234$), $t(109) = 3.01$, $p = .002$, $d = 0.287$, 95% CI [14, inf] (one-tailed), reflecting greater sustained arousal in an emotional context. Contrary to predictions, reward did not increase tonic pupil dilation, $F(1, 108) = 1.21$, $p = .274$, $\eta_p^2 = 0.011$

Table 1 Comparisons of mean correct response times (RTs, in ms) and accuracy (proportion correct) for scrambled versus intact images (distraction in milliseconds), for each distractor valence condition, separately for control and reward groups

Valence block	Scrambled trials	Intact trials	Distraction	d_z	95% CI	
					Low	Upper
Response times						
Control group						
Negative	669 (91)	813 (152)	144***(93)	1.550	119	169
Neutral	670 (81)	726 (112)	56***(49)	1.145	43	69
Positive	674 (94)	825 (160)	151***(93)	1.636	126	176
Reward group						
Negative	562 (100)	620 (140)	58***(60)	0.978	42	75
Neutral	564 (86)	598 (117)	34***(42)	0.824	23	46
Positive	568 (111)	631 (145)	63***(52)	1.204	49	77
Proportion correct						
Control group						
Negative	.965 (.036)	.947 (.052)	.018* (.055)	0.327	.003	.033
Neutral	.973 (.030)	.966 (.046)	.007 (.044)	0.156	−.005	.019
Positive	.969 (.025)	.926 (.070)	.043*** (.070)	0.631	.025	.063
Reward group						
Negative	.955 (.037)	.915 (.081)	.040*** (.072)	0.560	.021	.059
Neutral	.960 (.042)	.946 (.054)	.014* (.045)	0.314	.002	.026
Positive	.952 (.038)	.909 (.083)	.043*** (.075)	0.567	.063	.022

Note. Distraction is calculated as: [RT intact − RT scrambled] and [proportion-correct scrambled − proportion-correct intact]. Standard deviations are in brackets. Effect sizes are Cohen's d_z from paired comparisons of intact and scrambled trials within conditions, and asterisks indicate whether the intact − scrambled difference is significant in that condition. *$p < .05$, ***$p < .001$. 95% confidence intervals surround the distraction scores, in ms and proportion correct. $n = 55$ per group

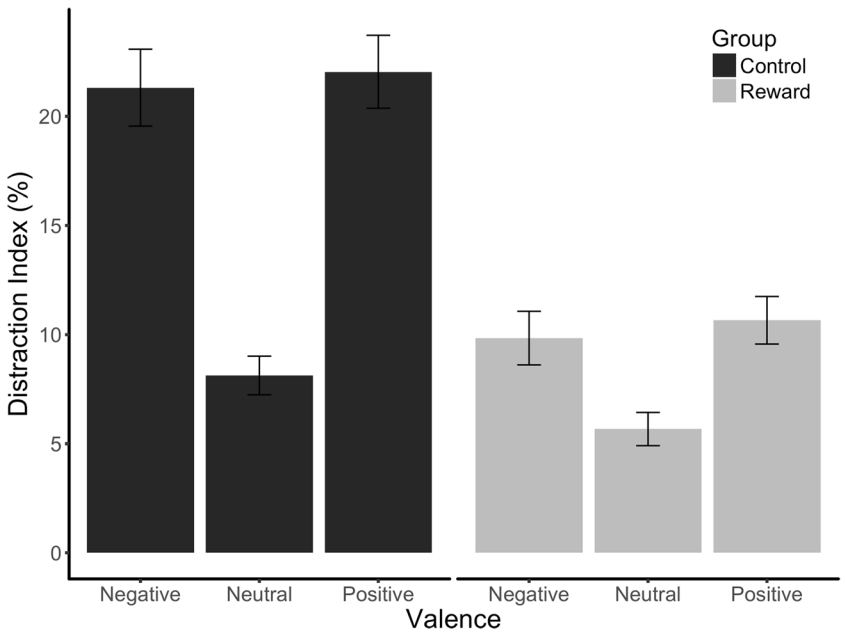

Fig. 2 Mean behavioural distraction indices by group and valence. Greater distraction [((mean RT intact − mean RT scrambled) / mean RT scrambled) × 100] was elicited by emotional than by neutral images. Neutral and (to a greater extent) emotional distraction were attenuated by reward. Error bars represent standard error of the mean

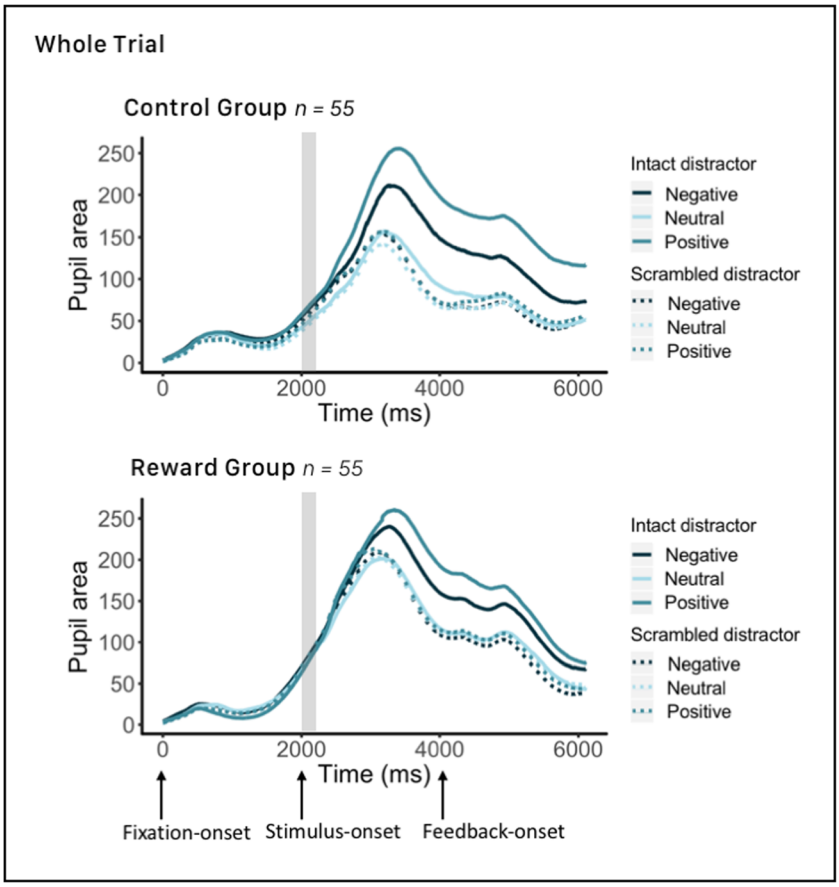

Fig. 3 Mean pupil area (in arbitrary units) across the entire trial. Dilation is subtraction-baselined to the mean during the 200-ms time window immediately preceding trial onset (on each trial) for the control group (top panel) and the reward group (bottom panel). Intact trials are represented by solid lines; scrambled images are represented by dotted lines. Distractor valence is represented by the different colour shades. Stimulus presentation (200 ms) is represented by the grey shaded area. Arrows indicate display onset for fixation, stimulus, and feedback. (Colour figure online)

(although numerically tonic dilation was higher in the reward group compared with the control group), and there was no Reward Group × Valence interaction, $F(2, 216) = 0.46$, $p = .629$, $\eta_p^2 = 0.004$; quadratic interaction: $F(1, 108) = 0.814$, $p = .369$, $\eta_p^2 = 0.007$. Thus, tonic dilation was modulated by emotional context, consistent with a shift to proactive control on emotional blocks (but see the Discussion section for an alternative explanation). However, tonic dilation was not modulated by reward group, suggesting that reward does not elicit sustained proactive control.

Table 2 Mean pupil area in arbitrary units (and *SD*) for preregistered tonic and phasic proactive time windows, for each distractor valence condition, separately for control and reward groups

Valence block	Tonic proactive control	Phasic proactive control
Control group		
Negative	−108 (242)	26 (33)
Neutral	−121 (240)	23 (26)
Positive	−90 (244)	24 (30)
Reward group		
Negative	−55 (209)	23 (28)
Neutral	−89 (228)	22 (26)
Positive	−42 (165)	20 (21)

Contrary to predictions, analysis of the phasic proactive control indices (reflecting preparation during the 2,000-ms fixation period preceding stimulus onset; see Fig. 5a) revealed no main effect of reward group, $F(1, 108) = 0.29$, $p = .591$, $\eta_p^2 = 0.003$, nor a Reward Group × Valence interaction, $F(2, 216) = 0.29$, $p = .748$, $\eta_p^2 = 0.003$; quadratic interaction: $F(1, 108) = 0.51$, $p = .476$, $\eta_p^2 = 0.005$. Also contrary to predictions, there was no effect of valence on phasic proactive control, $F(2, 216) = 0.70$, $p = .499$, $\eta_p^2 = 0.006$; quadratic: $F(1, 108) = 0.09$, $p = .766$, $\eta_p^2 = 0.001$. Here we see no evidence that participants dynamically prepare differently for an upcoming trial as a function of either reward group or valence of a potential distractor.

Poststimulus pupil indices An ANOVA was conducted on early and late poststimulus pupil indices (which reflect intact distractor processing relative to scrambled distractor

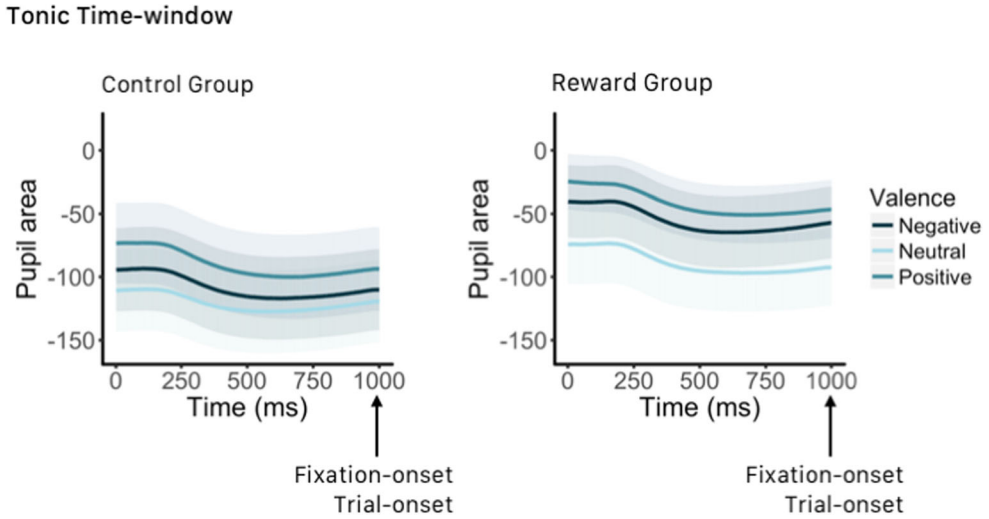

Fig. 4 Mean pupil area (in arbitrary units) across the tonic time window. Mean pupil area across the 1,000-ms time window preceding trial onset, subtraction-baselined to the mean during the 200-ms time window immediately preceding trial onset in the baseline (scrambled-image only, nonreward) block. Overall, there was greater tonic dilation (or, more accurately, less constriction relative to baseline) on emotional compared to neutral blocks (with no difference between tonic dilation on positive and negative blocks). Tonic dilation was not modulated by reward group. Shaded error bands represent the standard error

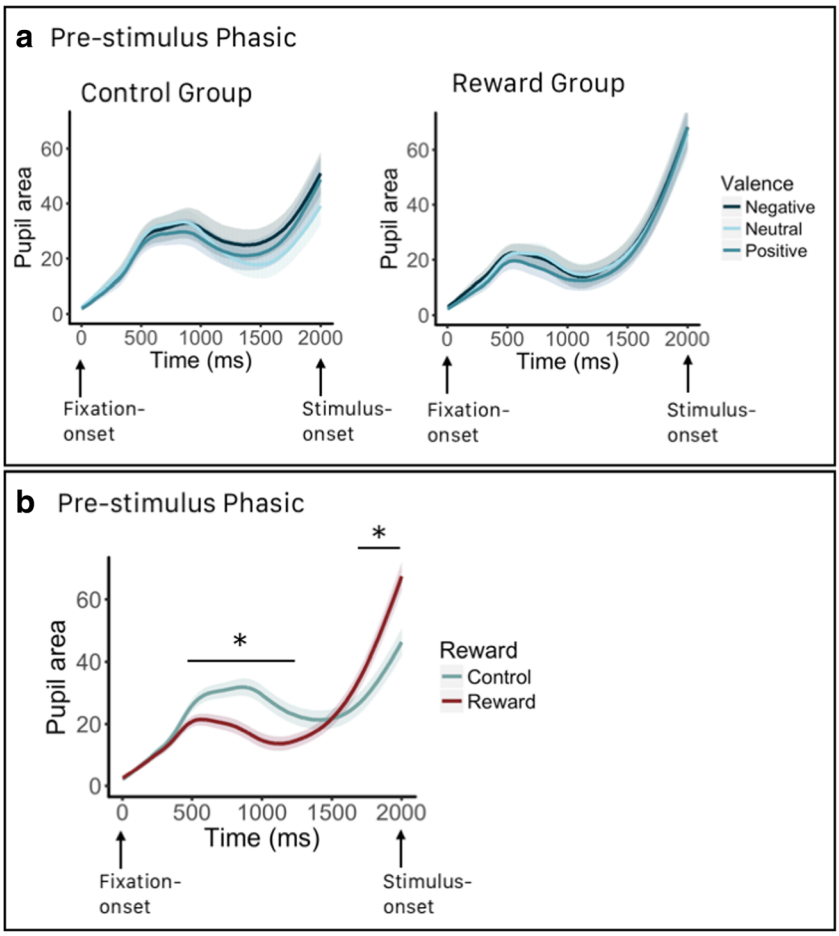

Fig. 5 Mean pupil area (arbitrary units) across the prestimulus phasic time window. **a** Phasic proactive control is indexed by mean pupil area during the 2,000-ms time window preceding stimulus onset, subtraction-baselined to the mean during the 200-ms time window immediately preceding trial onset. The preregistered analysis indicated no modulation of the mean phasic proactive control index (collapsed across the entire prestimulus time window) by either distractor valence or reward group. **b** Phasic pupil dilation collapsed by valence during the prestimulus 2,000-ms time window. Significant group differences from the functional *t* test are indicated by the horizontal lines and asterisks. Shaded error bands represent the standard error

processing) with valence (negative, neutral, positive) and time (early, late) as the within-subjects factors and reward group (reward, controls) as the between-subjects factor. We had no specific predictions regarding time. See Table 3 for means for each group, split by valence and time, and Fig. 6a for mean pupil area across the poststimulus time window.

The predicted quadratic main effect of valence indicated that emotional distractors produced greater pupil dilation than neutral distractors, $F(1, 108) = 108.50$, $p < .001$, $\eta_p^2 = 0.501$. Dilation in response to positive distractors ($M = 69$, $SD = 57$) was greater than for negative distractors ($M = 40$, $SD = 53$), $t(109) = 5.00$, $p < .001$, $d = 0.476$, 95% CI [17, 40] (two-tailed), so these were separately compared with neutral poststimulus pupil dilation (one-tailed). Pupil dilation following positive, $t(109) = 11.39$, $p < .001$, $d = 1.086$, 95% CI [55, inf], and negative, $t(109) = 6.40$, $p < .001$, $d = 0.610$, 95% CI [26, inf], distractors was greater than pupil dilation following neutral distractors ($M = 4$, $SD = 36$). The predicted Reward Group × Valence interaction was not significant, $F(2, 216) = 0.98$, $p = .378$, $\eta_p^2 = .009$; quadratic interaction: $F(1, 108) = 1.18$, $p = .280$, $\eta_p^2 = .011$, suggesting that (unlike for behavioural distraction) reward did not reduce pupil dilation in response to emotional distractors to a greater extent than neutral distractors.

A trend toward the predicted main effect of reward group on poststimulus pupil dilation, $F(1, 108) = 3.03$, $p = .084$, $\eta_p^2 = 0.027$, was qualified by a Time × Reward Group interaction (which was not predicted), $F(1, 108) = 4.16$, $p = .044$, $\eta_p^2 = 0.037$. To explore this interaction, two ANOVAs were conducted with valence as the within-subjects factor and reward group as the between-subjects factor, separately for the early and late time windows. This showed a significant effect of reward group on poststimulus pupil dilation in the early time window, $F(1, 108) = 6.93$, $p = .010$, $\eta_p^2 = 0.060$, but not in the late time window, $F(1, 108) = 0.74$, $p = .392$, $\eta_p^2 = .007$. The time course of the effect of reward group on poststimulus pupil dilation is further followed up in exploratory functional data analyses.

Table 3 Comparisons of mean pupil area for the preregistered poststimulus indices, for scrambled versus intact images, for each distractor valence condition, separately for control and reward groups

Valence block	Scrambled trials	Intact trials	Difference
Control group			
Early			
Negative	67 (57)	116 (85)	49 (50)
Neutral	67 (57)	79 (65)	12 (33)
Positive	72 (66)	155 (89)	83 (54)
Late			
Negative	14 (59)	55 (79)	41 (59)
Neutral	25 (71)	27 (77)	2 (51)
Positive	26 (71)	101 (82)	75 (64)
Reward group			
Early			
Negative	103 (58)	134 (74)	31 (47)
Neutral	102 (61)	104 (70)	2 (31)
Positive	106 (63)	165 (82)	59 (51)
Late			
Negative	20 (62)	57 (87)	37 (69)
Neutral	29 (66)	31 (70)	2 (38)
Positive	25 (79)	83 (93)	58 (67)

Note. Difference is [intact − scrambled]. Standard deviations are in brackets. $n = 55$ per group

Exploratory functional data analyses The following functional data analyses (FDA) are exploratory. Averaging pupil dilation across pre (or post) specified (albeit arbitrary) time windows is common in pupillometry studies (e.g., Bradley et al., 2008; Chevalier et al., 2015; Chiew & Braver, 2013, 2014; Cohen et al., 2015; Henderson et al., 2014; Rondeel et al., 2015), and we chose to use indices calculated from pupil area in preregistered time windows in keeping with these practices. However, in reducing the rich (1000 Hz) pupil data to mean dilation across long windows, we lose sensitivity to detect potential group differences in the time course of the implementation of control (see Sirois & Brisson, 2014, for discussion of this issue). FDA (see Ramsay & Silverman, 1997, 2005) solves this problem; the discrete pupil samples are converted into smooth functions, and then inferential statistics are performed on the functions over time. The output of a functional *t* test is a smooth function that defines the critical *t* value (and associated *p* value) at each time point; the advantage of this approach is that we can identify precisely if and *when* there are significant group differences (see Brisson et al., 2013; Jackson & Sirois, 2009, for use of FDA with pupillometry data). We conducted FDA only on the phasic prestimulus response and the poststimulus response, as these windows capture the dynamic changes in pupil dilation related to stimulus events. FDA is less appropriate for analysing tonic dilation, where the goal is to identify stable difference in overall levels of dilation. Because the analysis was exploratory, we did not restrict it to the preregistered windows, and so FDA was applied to two time windows, the first across the entire 2,000-ms prestimulus window (from fixation onset to stimulus onset), and the second across the entire 4,100-ms poststimulus onset window (from stimulus onset until the end of the ITI).

Following methods described by Ramsay and Silverman (1997, 2005), cubic B-splines were created for each participant, for each valence, for each time window, with a knot at each millisecond, and were smoothed by penalizing the second derivative. This creates a smooth curve that captures each participant's pupil response across time. The B-splines for individual participants were then collapsed across valence, and functional *t* tests were conducted to examine the time

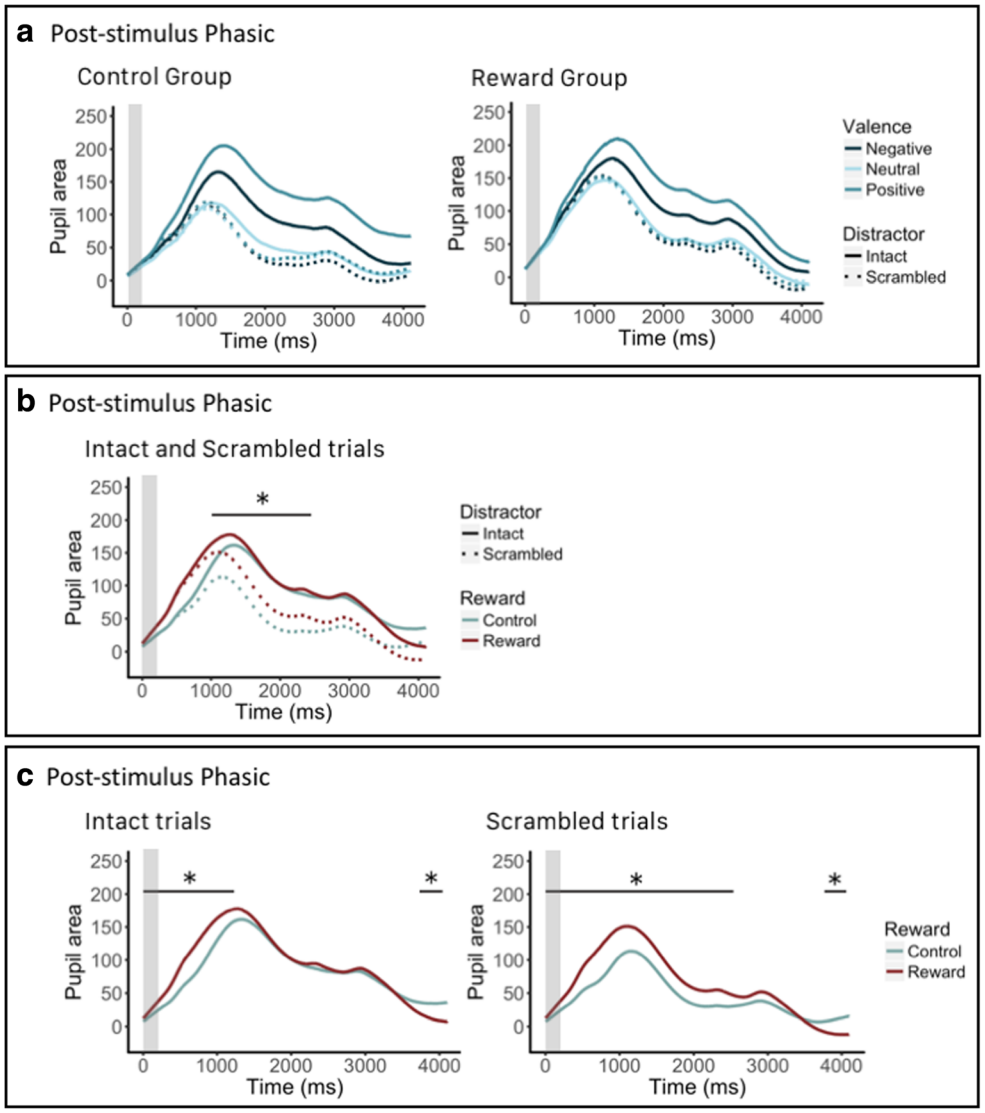

Fig. 6 Mean pupil area (arbitrary units) across the 4,100-ms post stimulus time window. All graphs show pupil area across the entire poststimulus period starting from stimulus onset (subtraction-baselined to the mean 200 ms prior to stimulus onset). **a** Pupil area split by valence, distractor type, and group (left: control group, right: reward group). Intact trials represented by solid lines; scrambled images represented by dotted lines. Distractor valence represented by different colour shades. Preregistered analyses of pupil indices from early and late poststimulus time windows showed modulation by both valence and reward group (see poststimulus pupil indices). **b** Pupil dilation, collapsed across valence, split by distractor type and reward group. Intact trials represented by solid lines, scrambled images represented by dotted lines. Reward group represented by different colours. Significant group differences for the intact − scrambled difference from the functional *t* test are indicated by the horizontal lines and asterisks. **c** Pupil dilation on intact trials (left), and scrambled trials (right), split by reward group. Significant group differences from the functional *t* test are indicated by the horizontal lines and asterisks. (Colour figure online)

course of group differences. To calculate the critical value of the test statistic, the labels of individual curves (for each participant, for each condition) were randomly shuffled, and then the test statistic was calculated with the new labels. One thousand permutations were run, resulting in a null distribution (the pointwise critical value over time) based on the actual data. (See OSF for plots of the functional *t* test output.)

Exploratory pupil proactive control functional t tests Visual inspection of the pupil data suggests that by averaging pupil dilation across the 2,000-ms time window prior to stimulus onset (our preregistered index of phasic proactive control), we missed important information about how proactive control unfolds across time, under conditions of reward relative to no reward (see Fig. 5a). Specifically, it appears that averaging across the time window might have disguised proactive control in the reward group that occurs close in time to stimulus onset. To address this possibility, we conducted a functional *t* test to determine whether (and when) this apparent group difference is significant. The timing of significant group differences are marked by asterisks on Fig. 5b. A significant group difference begins around 500 ms into the prestimulus period,

extending until 1,300 ms into the prestimulus period. However, contrary to predictions, this early difference is due to increased pupil dilation in the control group relative to the reward group, suggesting that the control group is implementing greater control than the reward group early in the fixation period. The second group difference occurs later, beginning around 1,750 ms (250 ms prior to stimulus onset) and extends until stimulus onset. This difference is in line with predictions, with the reward group showing greater pupil dilation, reflecting enhanced proactive control. Indeed, given that the reward group showed less dilation than the control group early in the pretrial window, their eventual greater dilation reflects a steep gradient in dilation just before stimulus onset. The functional *t* test reveals that the control and reward groups prepared to ignore the distractors over different time courses. Specifically, the control group exerted effort earlier, and less intensely, with a small boost of control close to stimulus onset. In contrast, the reward group prepared later, but more intensely, with a large dynamic boost of control close in time to stimulus onset.

Exploratory poststimulus pupil functional t tests In the preregistered poststimulus pupil ANOVA we found a trend toward the predicted main effect of reward group on poststimulus pupil dilation, which was qualified by a Time × Reward Group interaction. This interaction suggests an effect of reward group on pupil dilation elicited by the intact (relative to scrambled) distractors during some but not all of the poststimulus time period. To discover precisely when this group difference was significant, a functional *t* test was performed on the intact − scrambled difference in pupil area across the 4,100-ms time window, beginning at stimulus onset and extending to the end of the ITI period (subtraction-baselined to the 200-ms time window immediately preceding stimulus onset) comparing pupil area between the reward and control groups. This time window encompasses both the early and late preregistered poststimulus phasic pupil indices, as well as the 200-ms stimulus presentation and the 300-ms poststimulus offset periods which were not included in the preregistered time windows. The timing of significant group differences (extending from around 1,000 to 2,400 ms poststimulus) are marked in Fig. 6b.

Inspection of Fig. 6a suggests that, in addition to a reduction in the intact − scrambled difference in pupil dilation, there appears to be a shift toward greater pupil dilation in the reward group relative to the control group. To discover precisely

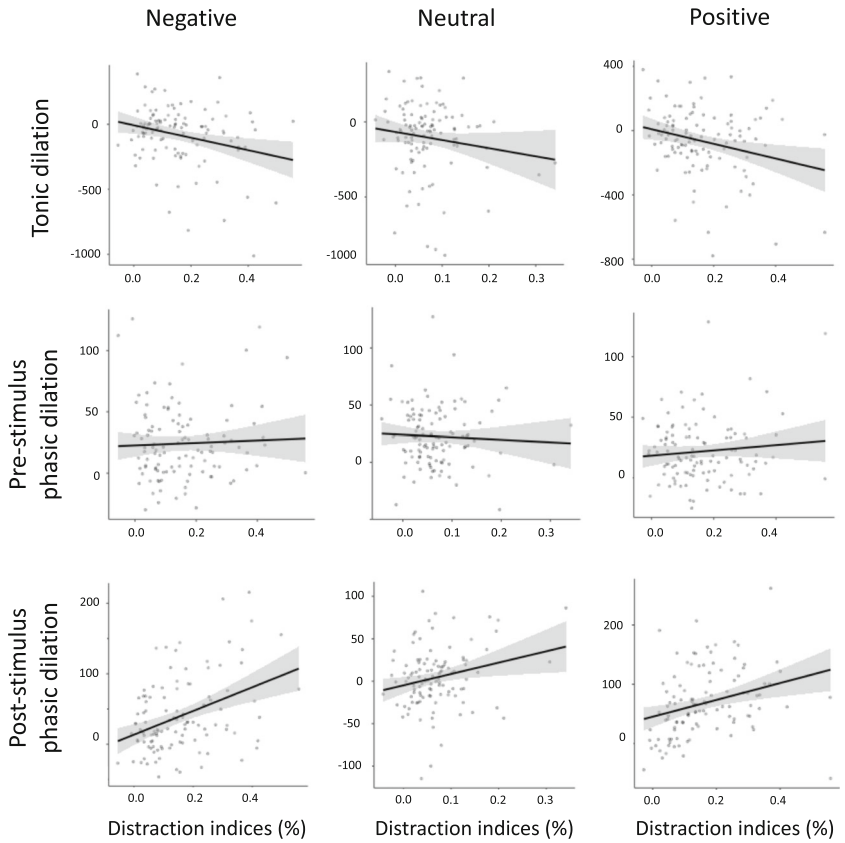

Fig. 7 Pupil indices − behavioural distraction correlations. Correlations between tonic (top row), prestimulus phasic (middle row), and poststimulus phasic (bottom row) mean pupil indices and behavioural distraction indices on negative (left column), neutral (middle column), and positive (right column) blocks. Significant positive correlations were found for poststimulus phasic pupil dilation (intact − scrambled difference) and behavioural distraction on positive and negative blocks. Significant negative correlations were found for tonic dilation and behavioural distraction for positive and negative blocks

when this group difference is significant, two functional *t* tests were performed comparing the poststimulus pupil dilation (separately for intact and scrambled trials, collapsed across valence) over the entire 4,100-ms poststimulus time window, to compare differences between the reward and control groups. For intact trials, there was greater pupil dilation in the reward group than in the control group for the first 1,200 ms of the poststimulus time window (marked in Fig. 6c, left graph). For scrambled trials, there was greater pupil dilation in the reward than the in control group for the first 2,550 ms of the poststimulus time window (marked on Fig. 6c, right graph). Thus, while reward decreased pupil responses to intact relative to scrambled images (suggesting a reduction in sensitivity to the content of images), it did so by *increasing* responses to scrambles to a greater extent than to intact images in the early time window. We return to the implications of this finding in the Discussion.

Exploratory pupil–behaviour correlations Nine exploratory correlations (see Fig. 7) were calculated to examine how pupil dilation relates to behavioural responses. We examined the relationship between each mean pupil index (tonic, phasic prestimulus, phasic poststimulus) and behavioural distraction indices, separately for each valence block (positive, negative, neutral). All significant correlations survived a Bonferroni correction (at alpha = .05, adjusted to .006 for nine tests) unless noted otherwise. First, to determine whether the phasic poststimulus intact − scrambled difference in pupil dilation does actually reflect processing of the emotional distractors, we examined correlations between phasic poststimulus dilation (averaged across the early and late time windows) and behavioural distraction. Positive correlations were significant for all three valences: negative blocks, $r(108) = .396$, $p < .001$; positive blocks, $r(108) = .296$, $p = .002$; and neutral blocks, $r(108) = .232$, $p = .015$. Note, however, that the correlation for neutral blocks does not survive the Bonferroni correction (corrected $p = .135$). These findings validate the poststimulus pupil dilation index as a measure of processing of the content of the emotional images, showing that the greater the pupil dilation following intact relative to scrambled images, the greater the behavioural distraction.

The tonic pupil index correlated negatively with emotional behavioural distraction, with greater tonic dilation on negative and positive blocks being associated with less negative, $r(108) = -.265$, $p = .005$, and positive, $r(108) = -.259$, $p = .006$, behavioural distraction, respectively. The correlation between tonic pupil dilation and behavioural distraction on positive blocks became marginal with the Bonferroni correction ($p = .054$). Tonic dilation on neutral blocks did not correlate with behavioural distraction, $r(108) = -.144$, $p = .134$. These findings are consistent with the interpretation that increased tonic dilation is associated with increased sustained control when distractors are expected to be emotional.

However, phasic proactive pupil dilation (collapsed across the 2,000-ms prestimulus time window) did not correlate with negative, $r(108) = .042$, $p = .664$, positive, $r(108) = .099$, $p = .302$, or neutral, $r(108) = -.053$, $p = .584$, behavioural distraction.[2]

Discussion

As predicted, the availability of performance-contingent reward decreased distraction by irrelevant images, particularly those that were emotional. These behavioural findings replicate our previous findings using a similar paradigm (Walsh et al., 2018) and are consistent with a growing body of evidence that motivation enhances cognitive control, even when distractors are highly emotional (Padmala & Pessoa, 2014; Padmala, et al., 2017). Mirroring the behavioural findings, and relative to scrambled control stimuli, emotional distractors produced greater dilation than neutral distractors, and dilation to distractors (relative to scrambled control images) was reduced by reward. Furthermore, greater poststimulus dilation to emotional distractors predicted greater behavioural emotional distraction, establishing pupil dilation as a valid measure of emotional processing that has behavioural consequences.

Our primary research question concerned the time course by which motivation reduces distraction. Specifically, we tested the hypothesis that reward encourages a shift to an effective proactive control strategy to ignore emotional distractors. We considered two variants of proactive control indexed by pupil dilation: dynamic up-regulation of control in preparation for an imminent distractor and sustained implementation of control across entire blocks. Although we found no evidence that reward modulated sustained proactive control, exploratory analyses showed dynamic implementation of proactive control close in time to stimulus onset in the reward group. Exploratory analyses also revealed that reward increased poststimulus dilation (regardless of distractor type), suggesting up-regulation of a reactive control mechanism. Together, these findings (examined in more detail below) suggest dynamic implementation of anticipatory control to more effectively disengage from distractors. We found no evidence that reward influences the time course of control differently for positive, negative, or neutral distractions.

We tested hypotheses using preregistered pupil indices (analysing baselined mean pupil area in specified time windows) and exploratory analyses using a more data-driven approach to identify time periods in which pupil dilation was

[2] Additional exploratory correlations were calculated between pupil dilation in the time windows that were sensitive to reward in the functional analyses (500–1,300 ms and 1,750–2,000 ms in the prestimulus time window) and behavioural distraction. These were calculated separately for the control and reward groups, and for each valence. None of these correlations reached significance (all *p*s > .107, uncorrected for multiple comparisons).

sensitive to reward. The tonic proactive control index (mean pupil area across the 1,000-ms period prior to trial onset) was greater in blocks in which distractors were emotional. It is difficult to determine whether this effect indicates greater sustained anticipatory control when emotional distractors were expected, or whether it is the result of emotional arousal carrying over from previously presented emotional distractors (which will have occurred on 25% of trials). One way to assess carryover would be to analyse trials that followed an intact distractor separately from those that followed a scramble; however, we did not have sufficient trial numbers to make such an analysis robust. The correlations with behaviour, however, argue against emotional carryover, because greater tonic dilation on emotional blocks was associated with *less* emotional distraction, consistent with the conclusion that tonic dilation is associated with enhanced sustained proactive control of emotional distraction. Emotional carryover, in contrast, would predict a positive relationship between tonic dilation and distraction on emotional blocks.

Importantly, the tonic proactive control pupil index was not affected by reward, nor did reward interact with valence. Findings therefore do not support the hypothesis that the availability of reward encourages the use of a sustained proactive control strategy in this task. Our findings contrast with those of Chiew and Braver (2013, 2014), who found that reward enhanced both tonic pupil dilation and behavioural proactive control. Our null effect of reward on sustained proactive control could be due to insufficient power; tonic pupil data have high variability, and numerically our reward group did show higher tonic dilation than controls. However, the significant effect of emotion on tonic dilation (greater tonic dilation in emotional compared to neutral blocks) suggests that our study did not lack power to detect cognitive effects on tonic dilation.

The preregistered phasic proactive control pupil index (mean pupil area across the 2,000-ms prestimulus window) was not modulated by valence, suggesting that similar dynamic proactive mechanisms were engaged preceding emotional and neutral distractions. Preregistered analyses also revealed no influence of reward on phasic proactive control. However, the exploratory functional *t* test showed a significant effect of reward, which arose because the time course of preparatory phasic pupil dilation differed between reward conditions. The test revealed (see Fig. 5b) an early window (from around 500 to 1,300 ms post fixation onset) in which pupil dilation was greater in control than in reward participants, and a late window (extending from around 1,750 ms after fixation onset and continuing until stimulus onset) in which phasic pupil dilation was greater (and rapidly increasing) in reward than in control participants. It appears that the control group exerted control earlier and less intensely than the reward group, who exerted a sharp "burst" of proactive control right before onset of the anticipated stimulus. This dynamic effect of reward on phasic proactive control is consistent with the effect of reward in nonemotional contexts (Chiew & Braver, 2013, 2014), and, indeed, reward did not interact with valence in any of our prestimulus analyses.

Turning to the poststimulus period, pupil dilation was modulated by both emotion and reward, in both the preregistered and exploratory analyses. Our preregistered analyses used indices of phasic poststimulus pupil dilation (mean pupil response to intact distractors relative to scrambles), to assess processing of the content of distractor images while controlling for low-level visual features. Although behavioural distraction and the pupil response to distractors were broadly similar (both were greater for emotional than for neutral distractors, and both were reduced by reward), there were some inconsistencies in the effects of valence. Pupil dilation was greater following positive (erotic) distractors than following negative (mutilation) distractors, which both produced greater dilation than neutral distractors. In contrast, behavioural distraction from positive and negative images did not differ (see also Walsh et al., 2018). The valence effect in the pupil response is consistent with findings from Henderson et al. (2014), showing greater pupil dilation to erotic images relative to negative images, even when they are matched for subjective ratings of arousal.

Behaviourally, reward produced greater attenuation of distraction in emotional blocks than in neutral blocks. This behavioural effect is consistent with the notion that, in addition to generally enhancing cognitive control (as reward does in emotionally neutral contexts), reward may reduce emotional distraction by additionally increasing the motivational value of the targets. If we attend to emotional distractors partly because we are motivated to attend to them, then enhancing the motivational value of targets might influence competition between targets and emotional distractors to a greater degree than between targets and neutral distractors (which lack this motivational value). However, this effect was not observed in the pupil index, which showed similar effects of reward on responses to emotional and neutral distractors.

Interestingly, further exploratory functional data analyses (FDA) showed that the effect of reward on post-stimulus dilation was driven primarily by *greater* dilation on trials with scrambled distractors (but to a lesser extent intact distractors) in rewarded participants compared with controls. This suggests a general, control-driven increase in dilation under reward. Separately examining the time course of group differences in dilation on intact trials, scrambled trials, and the intact − scrambled difference, allows us to make inferences regarding the respective influences of reward on control-related and emotion-related pupil dilation. Reward was associated with greater pupil dilation for both scrambles and intact images (regardless of valence) right from stimulus onset (see Fig. 6c). However, the effect of reward on the intact-scrambled difference did not emerge until about 1,000 ms later (see Fig. 6b). We suggest that the early effect of reward reflects

up-regulation of reactive cognitive control that is implemented in the face of any distractor. The later effect of reward reflects reduced emotional processing of distractors, due to more rapid implementation of control. The idea that there are separable cognitive and emotional influences on pupil dilation is not new. Dilation due to emotional arousal is thought to be under sympathetic control (Beatty & Lucero-Wagoner, 2000; Bradley et al., 2008), activating the pupil's dilator muscle; whereas dilation due to cognitive effort is the result of parasympathetic inhibition of the constrictor muscle (Samuels & Szabadi, 2008). Thus it is possible for cognitive control and emotional arousal to independently affect pupil size.

A similar dissociation between control-related and emotion-related pupil responses was recently described by Kinner et al. (2017). They observed pupil responses to neutral and negative images that participants viewed passively, or that they prepared to view under instruction to either up-regulate or down-regulate their emotional response. Pupil dilation in an early time window after image onset was enhanced in emotion-regulation conditions, regardless of whether the instruction required them to up-regulate or down-regulate their emotional response. It was not until a later time window that responses diverged, becoming larger in the up-regulation than in the down-regulation condition. Kinner and colleagues argue that early pupil responses reflect a 'cognitive' component, indexing the effort applied to both emotion regulation strategies, whereas later responses reflect an 'emotional' component that indexes the emotional consequences of that regulation. As described above, our findings could be similarly interpreted as showing an early effect of reward on pupil dilation, independent of the nature of the distractor, which reflects effortful control; followed by a later effect of reward on pupil dilation, dependent on distractor content, which reflects an emotional response. Considering that (in our data) reward enhances control-related dilation right from stimulus onset, this dilation may reflect a continuation of anticipatory control processes, or very fast activation of reactive control processes (e.g., disengagement), which continue long after stimulus offset and even behavioural response. Indeed, we can anticipatorily prepare to disengage from distractors (rather than proactively preventing their attentional selection; Theeuwes, 2010). Future research utilising other temporally sensitive measures, such as electroencephalography, may yield further insights into the time course of reward-based modulation of control of emotional distraction.

Although a decomposition of the pupil response into a cognitive and an emotional component provides a parsimonious explanation of our data, we cannot rule out an alternative explanation: that anticipation of reward induces emotional arousal that is reflected in the pupil response (e.g., Bouret & Richmond, 2015). At this point, we can say that poststimulus pupil responses were separately modulated by both reward and the emotional nature of the distractor. Manipulations that can tease apart the relative contributions of control and emotion on pupil dilation will be an important goal for future studies. We also note that analysis of the poststimulus pupil response in the late time window could be influenced by performance feedback (presented 2,000 ms poststimulus onset), which should be more affectively positive in the reward group than in the control group. However, group differences in the poststimulus pupil response (revealed by both the preregistered analyses and the exploratory FDA) were almost exclusively limited to the time window prior to feedback presentation, and therefore the potential affective influence of feedback does not impact our findings and conclusions.

Limitations in this study must be acknowledged. First, our findings in support of dynamic changes in proactive control were observed in the exploratory FDA, and not in our preregistered analyses using predefined windows. These exploratory findings therefore require replication with a preregistered analysis plan. Second, we limited our stimulus set to high-arousal negative (mutilation) and positive (erotic) images, because they are known to produce robust pupil responses. Extension to other stimulus categories, perhaps with different motivational value, will be necessary to determine how well these effects generalise. Third, our erotic image set included only heterosexual couples, and we did not ask participants about their sexual orientation. The subjective emotional value of both erotic and mutilation images naturally differs across people, with sexual orientation being one influencing factor. Although random assignment to reward groups should mean these individual differences will not account for our experimental effects, such variability might be useful to explore in future work. Finally, our neutral images were matched with the emotional images on content, and therefore contained people. The use of 'interesting' neutral images may have masked potential Reward × Emotion interactions that may emerge with the use of more mundane neutral distractors (e.g., household objects).

Attending to emotional stimuli is sometimes crucial for survival. But when emotional stimuli are neither imperative, nor relevant to current goals, we face the challenge of ignoring them. The current study sits at the intersection of the growing, but largely separate, literatures on the effect of reward on cognitive control in emotionally neutral contexts on the one hand, and the effect of (nonreward) control manipulations on emotional distraction on the other. Our findings confirm that performance-contingent reward can reduce emotional distraction, and suggest that it does so by dynamically up-regulating control just before the anticipated onset of a stimulus, and extending that control into the poststimulus period. We also show the value of pupillometry—a noninvasive and relatively low-cost tool—to further understanding of both emotion and cognitive control.

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Our experiment preregistration (osf.io/jd96p/), materials, data, analyses, and code are available on Open Science Framework: osf.io/yhkdr

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