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What our eyes tell us about feelings: Tracking pupillary responses during emotion regulation processes

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Abstract

Emotion regulation is essential for adaptive behavior and mental health. Strategies applied to alter emotions are known to differ in their impact on psychological and physiological aspects of the emotional response. However, emotion regulation outcome has primarily been assessed via self-report, and studies comparing regulation strategies with regard to their peripheral physiological mechanisms are limited in number. In the present study, we therefore aimed to investigate the effects of different emotion regulation strategies on pupil dilation, skin conductance responses, and subjective emotional responses. Thirty healthy females were presented with negative and neutral pictures and asked to maintain or up- and downregulate their upcoming emotional responses through reappraisal or distraction. Pupil dilation and skin conductance responses were significantly enhanced when viewing negative relative to neutral pictures. For the pupil, this emotional arousal effect manifested specifically late during the pupillary response. In accordance with subjective ratings, increasing negative emotions through reappraisal led to the most prominent pupil size enlargements, whereas no consistent effect for downregulation was found. In contrast, early peak dilations were enhanced in all emotion regulation conditions independent of strategy. Skin conductance responses were not further modulated by emotion regulation. These results indicate that pupil diameter is modulated by emotional arousal, but is initially related to the extent of mental effort required to regulate automatic emotional responses. Our data thus provide first evidence that the pupillary response might comprise two distinct temporal components reflecting cognitive emotion regulation effort on the one hand and emotion regulation success on the other hand.

Descriptors: Emotion regulation, Pupil dilation, Skin conductance responses, Emotional arousal, Peripheral physiology

Emotion regulation plays a pivotal role for mental health and interpersonal functioning (Gross, 2002; Gross & John, 2003). When emotion regulation is deficient or poorly matched to situational demands, emotional responses may be excessive, insufficient, or inappropriate. As a consequence, dysfunctional emotion regulation constitutes an important risk factor for the development and maintenance of psychological disorders (Eftekhari, Zoellner, & Vigil, 2009; Sheppes, Suri, & Gross, 2015). According to Gross (1998b), emotion regulation refers to all implicit or explicit physiological, behavioral, and cognitive processes that may be employed to change the occurrence, intensity, duration, or expression of an emotion. Different regulatory strategies can be applied that vary in when and how they influence the emotion-generative process (Gross, 2015). For instance, attentional deployment enables an individual to shift their focus away from an emotional cue (e.g., distraction), whereas cognitive change such as reappraisal aims at generating an alternative interpretation of an emotional situation (Gross, 2015). Due to the distinct temporal characteristics and the varying cognitive demands, emotion regulation strategies are suggested to have a differential impact on subjective emotional experience (Gross, 1998a; Van Dillen & Koole, 2007), neural responses (Kanske, Heissler, Schonfelder, Bongers, & Wessa, 2011; McRae et al., 2010; Ochsner & Gross, 2005), and psychophysiological reactivity of emotion (Jackson, Malmstadt, Larson, & Davidson, 2000; Kim & Hamann, 2012; Sheppes, Catran, & Meiran, 2009; Urry, 2010; Urry, van Reekum, Johnstone, & Davidson, 2009).

For instance, increased and decreased heart rate (Driscoll, Tranel, & Anderson, 2009; Kalisch et al., 2005) as well as facial corrugator activity (Ray, McRae, Ochsner, & Gross, 2010) were observed during reappraisal to up- and downregulate negative emotions, respectively. Similarly, emotion regulation effects have been demonstrated on skin conductance responses (SCRs) with both enhanced and reduced response patterns during regulation relative to control conditions (Feeser, Prehn, Kazzer, Mungee, & Bajbouj, 2014; Kim & Hamann, 2012; Matejka et al., 2013; Sheppes et al., 2009; Urry, 2009, 2010; Urry et al., 2009). Neuroimaging studies

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further imply that these changes are accompanied by increased brain activation in cognitive prefrontal control areas, which in turn modulate activity in emotion-processing systems such as amygdala and insula (Buhle et al., 2014; Dorfel et al., 2014; Feeser et al., 2014; Goldin, McRae, Ramel, & Gross, 2008; Kalisch, 2009; Kanske et al., 2011; McRae et al., 2010; Ochsner, Bunge, Gross, & Gabrieli, 2002). Importantly, experiments controlling participants' gaze direction revealed that emotion regulation success is not determined by general differences in attentional deployment (e.g., fixation on arousing versus neutral aspects of a situation; Bebko, Franconeri, Ochsner, & Chiao, 2014; Urry, 2010). Instead, it has been suggested that cognitive processes specific for the particular strategy caused the observed changes in autonomic physiology and subjective emotional ratings associated with emotion regulation success.

However, there are also quite a number of psychophysiological studies reporting no effects or rather a general, strategy-unspecific augmentation of arousal measures during emotion regulation (Dunn, Billotti, Murphy, & Dalgleish, 2009; Eippert et al., 2007; Gross & Levenson, 1997; Kim & Hamann, 2012; Ray et al., 2010). Due to these inconsistencies, the question remains whether differences between emotion regulation strategies can be reliably detected using classical measures of arousal.

Pupil diameter is known to be a physiological marker of sympathetic activation. The size of the pupil is determined by the relative activity of the two iris muscles, the sphincter and the dilator, which are controlled by the autonomic nervous system (Beatty & Lucero-Wagoner, 2000). Whereas pupil constriction is mainly driven by parasympathetic activity, pupil dilation is predominantly triggered by the sympathetic pathway (Andreassi, 2000). Accordingly, several studies have demonstrated that emotional arousal during affective picture viewing or auditory emotional stimulation is associated with enlarged pupil sizes (Bradley, Miccoli, Escrig, & Lang, 2008; Henderson, Bradley, & Lang, 2014; Janisse, 1974; Kret, Roelofs, Stekelenburg, & de Gelder, 2013; Partala & Surakka, 2003). Importantly, Bradley et al. (2008) could show that increases in pupil diameter covaried with other autonomic measures of arousal such as SCRs, implying that pupillary responses might serve as a reliable index of emotional arousal. In consequence, regulation processes that are invoked to modulate emotional responses should alter pupillary responses as well. However, findings are quite mixed with regard to whether changes in pupil diameter reflect emotional arousal or cognitive demand during emotion regulation.

For instance, Bebko et al. (2011) found diminished pupil sizes during emotion regulation, whereas other studies indicate that both increasing and decreasing negative emotions through reappraisal amplifies pupil dilation, most likely as a result of increased cognitive effort to regulate emotional responses (Johnstone, van Reekum, Urry, Kalin, & Davidson, 2007; Richey et al., 2015; Urry et al., 2006, 2009; van Reekum et al., 2007). Correspondingly, pupil size has been repeatedly found to increase in response to enhanced processing demands within a number of different tasks (Beatty, 1982; Beatty & Kahneman, 1966; Hess & Polt, 1964; Kuchinke, Vo, Hofmann, & Jacobs, 2007; Moresi et al., 2008; Prehn et al., 2008; Prehn, Heekeren, & van der Meer, 2011). Regarding emotion regulation, it might be reasonable to assume that pupil dilation reflects autonomic activation associated with both emotion regulation effort and emotion regulation success. In line with this notion, recent data revealed that larger pupillary responses during the anticipation of emotional stimuli predicted smaller pupil sizes during actual emotion processing (Vanderhasselt, Remue, Ng, & De Raedt, 2014). Interestingly, this temporal interplay was particularly observed in individuals habitually using reappraisal to regulate their emotions.

Task-evoked changes in pupil diameter typically occur within the first few hundred milliseconds after stimulus onset, with responses peaking at about 1 to 2 s and continuing quite asymptotically until they return to baseline values again (Andreassi, 2000; Beatty & Lucero-Wagoner, 2000; Loewenstein & Loewenfeld, 1962; Nieuwenhuis, De Geus, & Aston-Jones, 2011).This pattern suggests that the pupillary response may be separated into distinct temporal components. Contradicting findings regarding the impact of emotion regulation on pupil size might thus be attributed to differences related to the time interval chosen for the analysis of the pupillary response. Accordingly, some studies reported regulation effects to predominate on early (Bebko et al., 2011) or late pupil dilation (Urry et al., 2009), whereas others found both early and late effects depending on which strategy was applied (Urry et al., 2006; van Reekum et al., 2007). These inconsistencies point out that the relationship between emotion regulation and pupil dilation, particularly with respect to the temporal dynamics of the pupillary response, is still an unresolved issue.

In the present study, we therefore aimed to investigate the psychophysiological correlates of two different cognitive emotion regulation strategies, reappraisal (increase and decrease) and distraction, via the assessment of pupillary responses, SCRs, and subjective ratings during an emotional picture viewing task. In line with previous studies showing pupil size enlargements in response to cognitive control processes in general (see Beatty, 1982; Sirois & Brisson, 2014, for reviews) and emotion regulation demand in particular (Johnstone et al., 2007; Richey et al., 2015; Urry et al., 2006; van Reekum et al., 2007), we expected early pupil dilation (within the first 2 s of regulation) to be potentiated in all regulation conditions as compared to a viewing-only control condition, thus reflecting emotion regulation effort. Hypothesizing that late pupillary responses (from 2 s of regulation), in contrast, vary as a function of emotional arousal, we predicted larger pupil diameter when participants were required to increase negative emotional responses but smaller pupil sizes in the downregulation conditions (decrease, distract). According to this, late pupil dilation should serve as an indicator of emotion regulation outcome. Similarly, we expected SCRs to index emotional arousal (Bradley et al., 2008; Lang, Greenwald, Bradley, & Hamm, 1993) and therefore to show a pattern of decreasing activation across regulation conditions: increase > viewing only > distract, decrease (Urry et al., 2009). The inclusion of multiple measures of autonomic arousal in combination with subjective emotional ratings might help to disentangle regulation effects reflecting changes in emotional arousal from those reflecting changes in cognitive demand.

Method

Participants

A total of 30 healthy female students from the Ruhr-University Bochum ranging in age from 18 to 35 ($M = 24.4$, $SD = 4.95$) were recruited for participation in this study. Prominent sex differences have been observed in the processing of emotional stimuli (Bradley, Codispoti, Sabatinelli, & Lang, 2001; Canli, Desmond, Zhao, & Gabrieli, 2002), with women displaying a more pronounced subjective physiological and neuropsychological emotional reactivity (Lithari et al., 2010). Since a successful induction of negative emotions is a prerequisite to examine the impact of different emotion regulation strategies on emotional responses, only female participants were included. Exclusion criteria checked beforehand in a telephone interview comprised chronic or acute illnesses, any history of psychiatric or neurological treatment, drug use, and regular intake of medicine. All had normal vision, were fluent in German, and were not familiar with the stimuli used in the current paradigm.

Procedure

All experimental sessions were conducted in the afternoon in a moderately lit room. After participants received an explanation of the general procedure, they signed the informed consent form and filled out questionnaires on demographic data and current mood. Participants were then seated in an adjustable chair in front of the computer screen with a distance of 0.5 m at eye level, and were familiarized with the experimental paradigm by written instructions. Participants were asked to put on the eye-tracking glasses and to put their chin and forehead on a headrest to minimize head movements. Subsequently, the emotion regulation paradigm started. At the end of the experimental session, participants were reimbursed with €9 for their participation and received additional information regarding the aim of the study. All procedures conformed to the Declaration of Helsinki and were approved by the ethics committee of the Faculty of Psychology at the Ruhr-University Bochum.

Emotion Regulation Paradigm

A modified version of the emotion regulation paradigm (Kinner, Het, & Wolf, 2014) developed by Kanske et al. (2011) was applied. In this task, participants were instructed to view negative and neutral pictures (described below) or to regulate their upcoming emotional response toward negative pictures by means of three different emotion regulation strategies. In the decrease condition, participants were instructed to reduce the intensity of their emotional response by reappraising the displayed situation to happen either in a pleasant context or with a pleasant ending. The main goal of the increase condition was to intensify any emotional response elicited by the negative pictures, for example by imagining being the person depicted in the given situation and thinking of all the emotional and physical reactions that might occur or by thinking up a sad ending. Similar to previous studies (Kanske et al., 2011; McRae et al., 2010), the distract condition provided participants with an arithmetic problem, presented as a transparent overlay, and required them to decide whether the displayed solution was correct or incorrect. All arithmetic tasks were formed with two operands including a subtraction or an addition (e.g., $76 - 39 = 37$). In the viewing-only condition (referred to hereafter as view condition), participants attended to the content of the picture but did not manipulate their upcoming emotions to it. For each participant, 40 negative pictures were randomly assigned to the three regulation conditions and the view condition. To provide a neutral baseline condition, 10 neutral pictures were additionally presented in the view condition. Five experimental conditions were thus defined in total: view neutral, view negative, decrease, increase, and distract. Each trial started with a 750-ms presentation of an instructional cue (view, decrease, increase, calculate) indicating which strategy to apply, followed by a white fixation cross on a gray background displayed with a jitter of 2,500–5,000 ms. The picture was presented for 5,000 ms, serving as both the emotion induction and the emotion regulation phase. Subsequently, participants rated their emotional response on a 9-point visual analog scale for subjectively experienced arousal (ranging from *quiet* to *active*) and valence (ranging from *unpleasant* to *pleasant*). Rating scales were displayed consecutively for 5,000 ms each or until the participant had responded via mouse click. In the distract condition, participants further had to indicate whether the equation was correct or incorrect after they had rated their emotional response. Feedback on the response accuracy was not provided. Intertrial intervals depicting a black screen were randomly jittered between 2,500 and 5,000 ms. To ensure that participants were able to apply the instructed emotion regulation strategies properly, oral practice trials were carried out before the computer task together with the experimenter. To get accustomed to the apparatus and especially to the structure of the experimental trials, eight computer-based practice trials were then additionally conducted before the emotion regulation paradigm started. Figure 1 illustrates the sequence of events in a trial. Trial order was pseudorandomized with no more than two equal conditions in succession. In total, the paradigm consisted of 50 trials (10 trials per condition) and lasted about 25 min. Stimulus presentation and behavioral recording were controlled by MATLAB R2012a (MathWorks Inc., Natick, MA) on an IBM compatible PC running on Windows 7.

Stimuli

Pictures were selected from the International Affective Picture System (IAPS) based on normative ratings (Lang, Bradley, & Cuthbert, 2008). Sets of 40 negative pictures (valence: $M = 2.70$, $SD = 0.59$; arousal: $M = 5.61$, $SD = 0.84$) and 10 neutral pictures (valence: $M = 5.06$, $SD = 0.30$; arousal: $M = 3.32$, $SD = 0.48$) were created. Arousal and valence ratings differed significantly between the sets (both $ps < .001$). All pictures were landscape ($1{,}024 \times 768$ pixels) in orientation, matched for content and complexity, and were displayed in grayscale. Mean luminosity of the selected pictures was matched using the MATLAB R2012a SHINE toolbox (MathWorks Inc.) such that the mean and distribution of luminosity values for the two picture sets did not differ (negative: $M = 57.64$, $SD = 1.08$; neutral $M = 57.40$, $SD = 1.23$, $p > .50$; Willenbockel et al., 2010). To control the level of illumination prior to picture onset, a white fixation cross on a gray background (2,500–5,000 ms) with the mean luminosity computed across all pictures preceded picture presentation on each trial.

Pupillometry

Pupillary data were recorded with iView eye-tracking glasses (iViewETG 2.0, SensoMotoric Instruments, Germany) connected to an SMI-ETG recording device (Lenovo X230-Notebook) compatible to the iViewETG software. A high-definition scene camera including an infrared-sensitive eye camera for dark pupil detection measured retinal and corneal reflections to obtain participants' pupil diameter of the left and the right eye. Pupillary data were recorded at a binocular sampling rate of 30 Hz, a gaze tracking range of 80° horizontal and 60° vertical visual angle, and a gaze position accuracy of 0.5°. A one-point calibration was carried out to ensure that the participants' eyes were correctly tracked by the iView System. Due to technical failure, two participants were excluded from analysis as data could not be stored.

Analysis of pupillary data. Pupillary data were prepared and pre-analyzed using the behavioral and gaze analysis (SMI BeGaze)

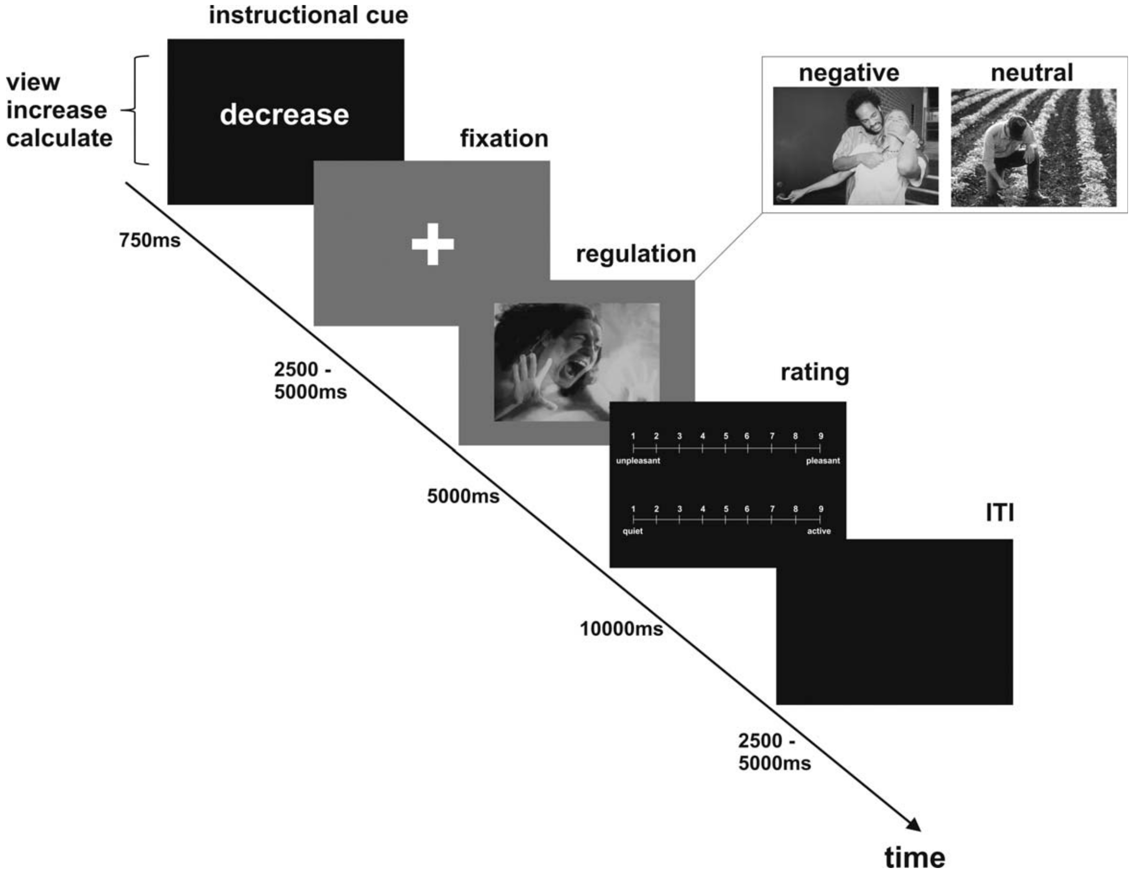

Figure 1. Sequence of events in a trial in the emotion regulation paradigm. Participants were asked to simply look at neutral or negative pictures (view condition) or to regulate their upcoming emotional response toward negative pictures with the help of three different emotion regulation strategies (distract, increase, decrease). Ratings of subjective valence and arousal were assessed directly after each picture presentation.

software. Recorded data were averaged across both eyes, smoothed with a finite impulse response filter at 6 Hz, and onsets of event-locked segments (instructional cue, fixation cross, picture presentation) were marked for each trial. A MATLAB-based algorithm was used to discard trials with major blinks (> 100 ms) and to correct trials with smaller artifacts by linear interpolation. For each participant and each individual trial, baseline pupil size was defined as the average pupil diameter recorded during the 300 ms prior to picture onset, and was subtracted from the pupil dilations during picture presentation to gain comparable pupillary response indices. Preliminary examination of individual trials revealed a typical pupillary response curve with an immediate constriction of the pupil at about 0.5 to 1 s (initial light reflex; Beatty & Lucero-Wagoner, 2000) and a peak dilation between 1 and 2 s after stimulus onset that continued fairly asymptotically over the course of picture presentation (see Figure 2). According to our theoretical considerations concerning an early cognitive and a late emotional pupillary response component (see introduction), two temporally distinct averaged pupil dilation measures were computed separately for each participant and experimental condition. Based on the typical onset latency and temporal continuation of the pupillary response curve (Andreassi, 2000; Beatty & Lucero-Wagoner, 2000; Loewenstein & Loewenfeld, 1962; Nieuwenhuis et al., 2011) and similar to previous pupillometric studies (Bebko et al., 2011; Bradley et al., 2008; Henderson et al., 2014; Urry et al., 2009), the early pupillary response was defined as the peak dilation in the interval between picture onset and 2 s. A gradient was calculated between the minimum pupil diameter between 0 and 1 s after picture onset and the maximum pupil diameter between 1 and 2 s after picture onset (see Bradley et al., 2008; Henderson et al., 2014). The late pupillary response was determined as the pupil diameter increase within the interval between 2 and 5 s after picture onset (see Bebko et al., 2011; Bradley et al., 2008; Henderson et al., 2014, for similar time intervals). To selectively capture only late pupillary responses that are not confounded by early cognitive processes, the area under the curve with respect to increase (AUC_I) was computed (see Kuchinke, Schneider, Kotz, & Jacobs, 2011; Pruessner, Kirschbaum, Meinlschmid, & Hellhammer, 2003). In addition, the area under the curve with respect to ground (AUC_G) was created as a measure of total pupil diameter increase for a comparison with previous pupillometric studies on emotion processing and emotion regulation (Bebko et al., 2011; Bradley et al., 2008; Henderson et al., 2014; Urry et al., 2006; van Reekum et al., 2007). For each condition, individual pupillary data were averaged across the 10 trials. Figure 3 displays the three different formulas for the computation of the early and late pupillary response component on an exemplary pupillary response curve.

Skin Conductance Responses

SCRs were sampled at a sampling rate of 1000 Hz with a commercial SCR coupler and amplifying system (MP150 + GSR100C, BIOPAC Systems, Inc.; software: AcqKnowledge 4.2) using Ag/AgCl electrodes filled with isotonic (0.05M NaCL) electrolyte

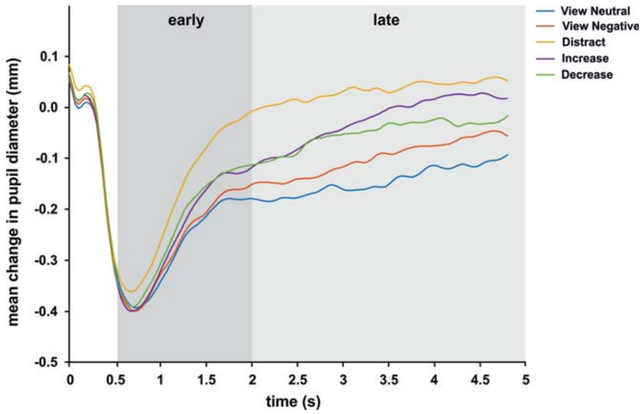

Figure 2. Task-evoked mean pupillary responses to neutral and negative pictures in the view condition and the three emotion regulation conditions (distract, increase, decrease). The early interval response (0.5–2 s) is highlighted in dark gray and the late interval response (2–5 s) in light gray.

medium (Synapse Conductive Electrode Cream) attached to the hypothenar of the nondominant hand. Raw SCR data were high-pass filtered with a cutoff frequency of 0.05 Hz. SCRs were defined as the maximum amplitude (in µS) within a window of 1–8 s after picture onset and calculated as the baseline-to-peak amplitude difference of the largest deflection within a window of 1–8 s after picture onset. The baseline was the skin conductance level immediately preceding the inflection point (Hamacher-Dang, Merz, & Wolf, 2015; Meir Drexler, Merz, Hamacher-Dang, Tegenthoff, & Wolf, 2015;

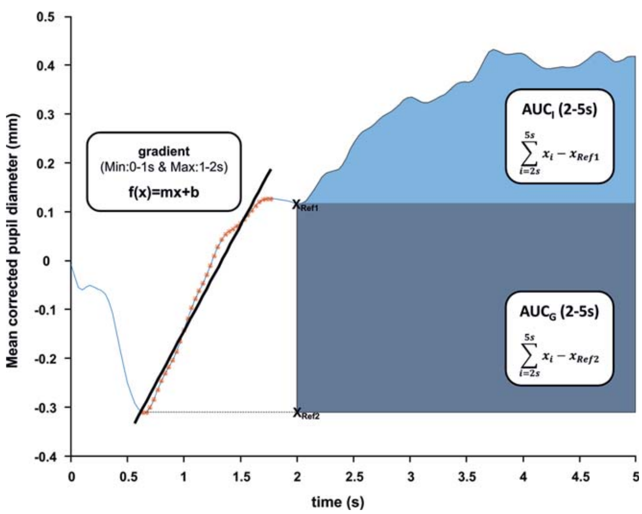

Figure 3. The three formulas for the computation of the early and late pupillary response components are displayed on an exemplary pupillary response curve. For the early pupillary response (left side), a gradient was calculated between the minimum pupil diameter between 0 and 1 s after picture onset and the maximum pupil diameter between 1 and 2 s after picture onset. The late pupillary response (right side) was determined as the total pupil diameter increase within the time interval of 2 and 5 s after picture onset. The area under the curve with respect to increase (AUC_I; light blue) and the area under curve with respect to ground (AUC_G; combined area [light and dark blue] indicated by the surrounding black line) were computed as measures of pupil size increase. $X_{Ref1} = x$ (2 s), baseline is defined as the first data point at 2 s; $X_{Ref2} = \min(x)$, baseline is defined as the minimum pupil diameter between 0 and 1 s.

Merz, Hamacher-Dang, & Wolf, 2014). Data were transformed with the natural logarithm to attain a normal distribution. For each condition, individual SCRs were averaged across the 10 trials.

Statistics

All statistical analyses were performed using IBM SPSS 22 Statistics for Windows with the level of significance set to $\alpha = .05$. For behavioral data (arousal and valence ratings), as well as for the physiological data (pupillary data and SCRs), we conducted analyses of variance (ANOVA) with the within-subject factor condition (view neutral, view negative, decrease, increase, distract). Greenhouse-Geisser-corrected p values and degrees of freedom were reported if the assumption of sphericity was violated. Effect sizes of significant results are reported as proportion of explained variance (η_p^2, partial eta squared). To determine differences between the conditions, three nonorthogonal planned comparisons using the error term from the overall ANOVAs (Braver, MacKinnon, & Page, 2003) were conducted for each measurement: arousal, late pupillary response (AUC_I, AUC_G), and SCRs: (1) neutral < negative, (2) negative > (decrease, distract), (3) negative < increase; valence: (1) neutral > negative, (2) negative < (decrease, distract), (3) negative > increase; early pupillary response: (1) neutral vs. negative, (2) negative < (decrease, distract), (3) negative < increase (Bonferroni corrected $\alpha = .033$, one-tailed; for the early pupillary response contrast neutral vs. negative, the level of significance was set to $\alpha = .0167$, two-tailed). If indicated by the data, additional exploratory Bonferroni-corrected post hoc t tests using the error term from the overall ANOVAs were conducted (Braver et al., 2003). Performance-based exclusion of participants is sometimes used in studies on emotional learning and memory (Schiller et al., 2008; Schiller, Kanen, LeDoux, Monfils, & Phelps, 2013) as well as in emotion regulation studies using psychophysiological measures (Dunn et al., 2009; Urry, 2009, 2010; Vujovic, Opitz, Birk, & Urry, 2014). Since the view neutral condition served as a baseline measure to compare with emotional and regulated emotional responses, we included only participants who showed a relatively low emotional response to neutral stimuli. Outliers in this condition were identified if the mean subjective or physiological response to neutral pictures was higher than 1.5 interquartile ranges above the third quartile of the group mean (Meir Drexler et al., 2015). According to this criterion, two participants were excluded from the analysis of the AUC_I, one for AUC_G analyses, and five participants from SCR analyses. For the analyses of the early pupillary response and subjective data, no participants were excluded. Power values for the relevant statistical analyses are specified according to Hager (2004): The hypothesis comprises a main effect of condition (within-subject factor, five levels). With a sample size of 30 participants, a given significance level of .05, and an assumed population correlation (supported by our empirical data) of at least $p = .50$ for respective repeated measurements, this main effect can detect a medium effect of $\Omega^2 \geq .06$ with a probability of 1-β (statistical power) > .90. All power calculations were done with G*POWER3 (Faul, Erdfelder, Lang, & Buchner, 2007).

Results

Subjective Ratings

ANOVA for valence and arousal ratings were conducted to explore the impact of different emotion regulation strategies on subjective emotional responses toward the neutral and negative pictures. As

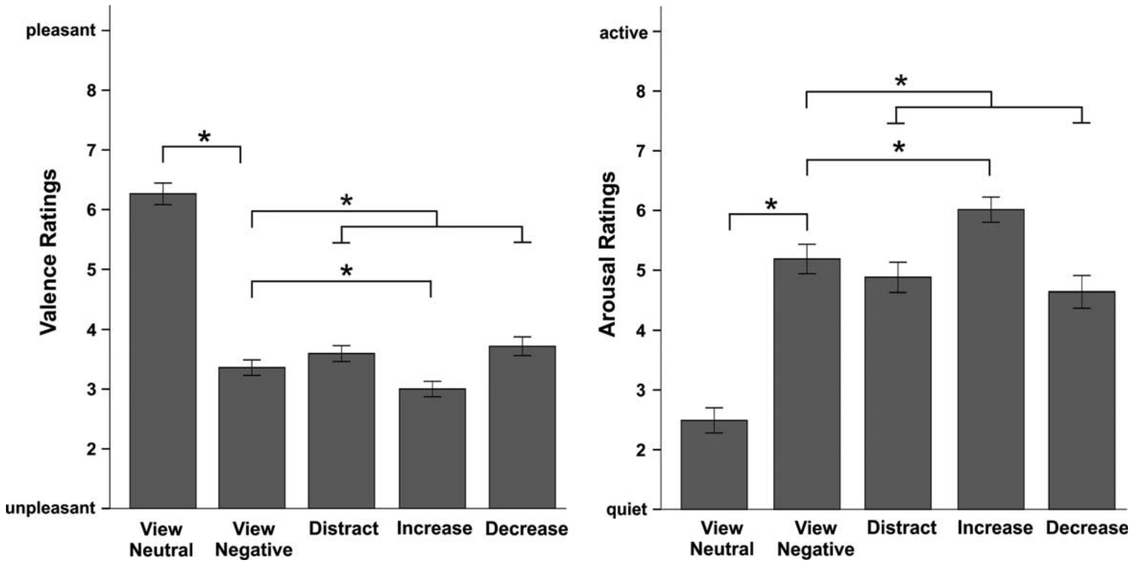

Figure 4. Mean (± *SEM*) subjective valence and arousal ratings to neutral and negative pictures in the two view conditions and the three emotion regulation conditions (distract, increase, decrease). In the view conditions, neutral pictures were rated as significantly less unpleasant and less arousing than negative pictures. Moreover, emotion regulation had a significant impact on emotional ratings. In the increase condition, negative pictures were rated as more unpleasant and arousing, whereas valence was higher and arousal lower in the downregulation conditions (decrease, distract) when compared to the view condition. *$p < .033$ (Bonferroni-corrected planned comparisons).

Figure 4 illustrates, significant differences in subjectively experienced valence and arousal occurred between the different conditions (main effect of condition valence: $F(2.3,67.5) = 101.36$; $p < .001$; $\eta_p^2 = .78$; main effect of condition arousal: $F(3.1,89.0) = 66.61$; $p < .001$; $\eta_p^2 = .70$). Planned comparisons revealed that subjective valence and arousal were modulated by the emotional content of the pictures, as participants rated neutral pictures as significantly more pleasant and less arousing than negative pictures in the view condition (both ps $< .001$; Figure 4; Table 1). Moreover, a differential impact of the emotion regulation strategies on subjective emotional responses was observed. Negative pictures were rated as significantly more unpleasant and more arousing when participants had to increase their emotional response, but significantly less unpleasant and less arousing when they were instructed to downregulate their emotional responses (decrease, distract) when compared to the view condition (all $ps < .01$; Figure 4, Table 1).

Early Pupillary Response

To determine whether the early pupillary response was modulated by emotion regulation processes, an ANOVA with the gradient values for each condition was conducted. Analyses revealed a significant main effect of condition, $F(4,108) = 3.85$; $p < .01$; $\eta_p^2 = .13$. As indicated by planned comparisons, early pupil dilation was significantly greater in all regulation conditions compared to viewing negative pictures (all ps $< .01$; Figure 5A; Table 1). However, the early pupillary response did not differ between viewing neutral and negative pictures ($p = .45$).

Late Pupillary Response

Significant differences between the conditions were also observed for the late pupillary response as determined by the AUC_I (main effect of condition: $F(3.0,74.6) = 5.91$; $p = .001$; $\eta_p^2 = .19$; Figure 5B; Table 1). Late pupil dilation was significantly enhanced when viewing negative pictures as compared to viewing neutral pictures ($p < .01$), indicating an effect of emotional arousal on late pupillary responses. Moreover, increasing emotional responses toward negative pictures led to greater pupil sizes relative to the view condition ($p < .001$). However, downregulation of negative emotions (decrease, distract) did not differ from the view condition ($p = .30$). Since AUC_I values for the two downregulation conditions differed descriptively from each other and the increase condition (see Figure 5B), three post hoc tests (Bonferroni-corrected $\alpha = .0167$, two-tailed) were carried out to further characterize these differences. Pupil dilation was potentiated when increasing negative emotional responses relative to both the distract ($p = .001$) and decrease condition ($p = .01$). However, the comparison between the distract and view condition revealed no significant difference ($p = .47$).

A significant main effect of condition was also found for the AUC_G measure, $F(4,104) = 13.41$; $p < .001$; $\eta_p^2 = .34$ (Table 1). Again, viewing negative pictures elicited a more pronounced pupil size increase than viewing neutral pictures ($p < .01$). Likewise, late pupil diameter was significantly enhanced in the increase condition when compared to the view condition ($p < .001$). In contrast to the AUC_I measure, however, this time downregulation also differed significantly from the view condition ($p < .001$). Post hoc tests (Bonferroni-corrected $\alpha = .0167$, two-tailed) further indicated that both distract and decrease resulted in a potentiation of late pupillary responses relative to the view condition (all ps $< .01$). This potentiation was more pronounced in the distract condition than in the decrease condition ($p < .002$).[1]

SCR

ANOVA for the SCRs showed a significant main effect of condition, $F(4,96) = 2.87$; $p < .05$; $\eta_p^2 = .11$. Planned comparisons

1. Three additional analyses for late pupillary responses were conducted based on measures developed in previous pupillometric studies on emotion regulation (Bebko et al., 2011; Bradley et al., 2008; Urry et al., 2006). Results were highly similar to those obtained with the AUC_G measure.

Table 1. *Self-Reported Valence and Arousal Ratings, Early (*Gradient) and Late Pupil Dilation *(*AUC_I*;* AUC_G*), and Skin Conductance Responses (*SCRs) to Negative and Neutral Pictures *(M ± SEM)*

	View neutral	View negative	Distract	Increase	Decrease
Valence	6.27 ± 0.18	3.36 ± 0.13	3.60 ± 0.13	3.00 ± 0.13	3.72 ± 0.16
Arousal	2.49 ± 0.21	5.19 ± 0.25	4.88 ± 0.25	6.01 ± 0.21	4.64 ± 0.27
Gradient	0.27 ± 0.02	0.27 ± 0.03	0.34 ± 0.03	0.32 ± 0.03	0.34 ± 0.03
AUC_I	2.01 ± 0.78	4.25 ± 0.84	3.62 ± 1.26	7.67 ± 0.93	5.34 ± 1.14
AUC_G	22.72 ± 1.84	26.91 ± 2.39	34.06 ± 2.91	32.46 ± 2.86	30.03 ± 2.77
SCRs	0.07 ± 0.02	0.11 ± 0.02	0.11 ± 0.02	0.13 ± 0.02	0.11 ± 0.03

Note. In each condition, 10 negative pictures were presented. In the view condition, 10 neutral pictures were additionally shown (view neutral). Valence: 1 = *unpleasant*, 9 = *pleasant*. Arousal: 1 = *quiet*, 9 = *active*. Gradient = mm/s; AUC_I = mm; AUC_G = mm; SCRs = [ln(1 + μS)].

revealed that responses to the negative pictures were significantly higher than to neutral pictures in the view condition ($p < .01$; Figure 5C; Table 1), indicating an impact of emotional arousal on SCRs. Again, SCRs were highest when increasing negative emotions. However, when compared to viewing negative pictures, this difference was only apparent as a trend ($p = .05$). Likewise, SCRs did not differ between the downregulation conditions and the view condition ($p > .49$), indicating that SCRs in general were not modulated by emotion regulation processes.[2]

Discussion

In the current study, we investigated the impact of different emotion regulation strategies on subjective and psychophysiological emotional responding during a picture viewing task. Subjective ratings indicated that emotional responses toward negative pictures were effectively up- and downregulated through cognitive reappraisal and distraction as compared to a view control condition. Furthermore, a differential impact of emotion regulation on early and late pupil dilation was observed, suggesting that the pupillary response might comprise two distinct temporal components reflecting cognitive and emotional processes involved in emotion regulation.

As expected, emotion induction via negative picture presentation was successful, as evidenced by decreased valence and increased arousal ratings compared to neutral pictures (Lang et al., 2008). This effect of unregulated emotional arousal was further supported by enlarged pupil sizes and SCRs when participants viewed negative relative to neutral pictures. Consistent with this, previous studies have demonstrated that emotional arousal increases pupil diameter (Bradley et al., 2008; Kret et al., 2013; Partala & Surakka, 2003) and SCRs (Eippert et al., 2007; Khalfa, Isabelle, Jean-Pierre, & Manon, 2002; Urry, 2009; Vujovic et al., 2014) as well as other autonomic measures (Jackson et al., 2000; Vujovic et al., 2014). For the current study, however, it is important to note that only late pupillary responses, not early peak dilations, were modulated by picture emotionality. Similarly, Partala and Surakka (2003) reported that emotion-induced alterations in pupil dilation occurred at 1–2 s after stimulus onset, whereas no such differences could be observed during the first 400 ms of the pupil's response. In line with that, Bradley et al. (2008) predefined a time interval from 2–6 s after picture onset for the analysis of emotional pupillary responses without considering the initial component. Accordingly, Gross (2015) proposed that emotions unfold over seconds to minutes, giving rise to a number of changes in experiential, behavioral, and physiological response systems. In line with our hypothesis, the late component of the pupillary response might therefore particularly reflect autonomic arousal related to the experience of emotions.

Importantly, pupil size was further modulated by emotion regulation processes. For the early response component, a general potentiation of pupil size occurred during the regulation of negative emotions, regardless of whether participants tried to increase or decrease emotions or distract themselves from the displayed emotional scene. Consistent with this, a number of previous studies has demonstrated that increasing task load (Beatty, 1986; Beatty & Kahneman, 1966; Hess & Polt, 1964; Kuchinke et al., 2007; Moresi et al., 2008; Prehn et al., 2008, 2011) and cognitive emotion regulation (Johnstone et al., 2007; Urry et al., 2006, 2009; van Reekum et al., 2007) lead to pupil size increases. Our results thus add to the existing evidence that the pupil dilates as a function of cognitive effort required to voluntarily regulate emotional responses.

Furthermore, our data revealed that these effects particularly occurred within the first pupillary response interval, indicating that the attempt to cognitively regulate emotions might be expressed relatively quickly in pupil diameter. In line with these findings, early pupillometric studies already showed that memory load is associated with extremely rapid dilations that typically occur within the first second after cue onset (Beatty & Kahneman, 1966). In addition, characteristics of the emotion regulation paradigm might account for this specific temporal pattern. In the present study, participants received the respective regulation instruction shortly before emotional picture presentation, and thus might have used this anticipation phase to directly counteract the upcoming emotional response as soon as the picture was displayed. This rapid activation of regulation resources may, in turn, have led to the fast dilation of the pupil. The timing of instruction may therefore also explain the heterogeneous findings regarding cognitive regulation effects on early versus late time intervals. In line with this presumption, enhanced pupil dilation during middle or late regulation periods had been specifically observed in studies in which the

2. For subjective ratings and psychophysiological measures, additional ANOVAs were conducted on difference scores between the baseline condition (view neutral), the negative emotion condition, and the three emotion regulation conditions, respectively (view negative-baseline, distract-baseline, increase-baseline, decrease-baseline). ANOVAs for subjective valence and arousal as well as for early and late pupil dilation again revealed a significant main effect of condition (valence: $p < .001$; arousal: $p < .001$; early pupil dilation: $p < .05$; late pupil dilation: $p < .05$), confirming the results that we have formerly obtained in the original analyses. Likewise, the specific result pattern for up- and downregulation was confirmed by planned comparisons (all $ps < .01$, except for the comparison between view negative-baseline and downregulation-baseline ($p = .29$) in the AUC_I measure). For SCRs, the main effect of condition did not reach significance ($p = .58$), again indicating that SCRs were not modulated by emotion regulation but rather reflect emotional arousal in response to the negative stimuli.

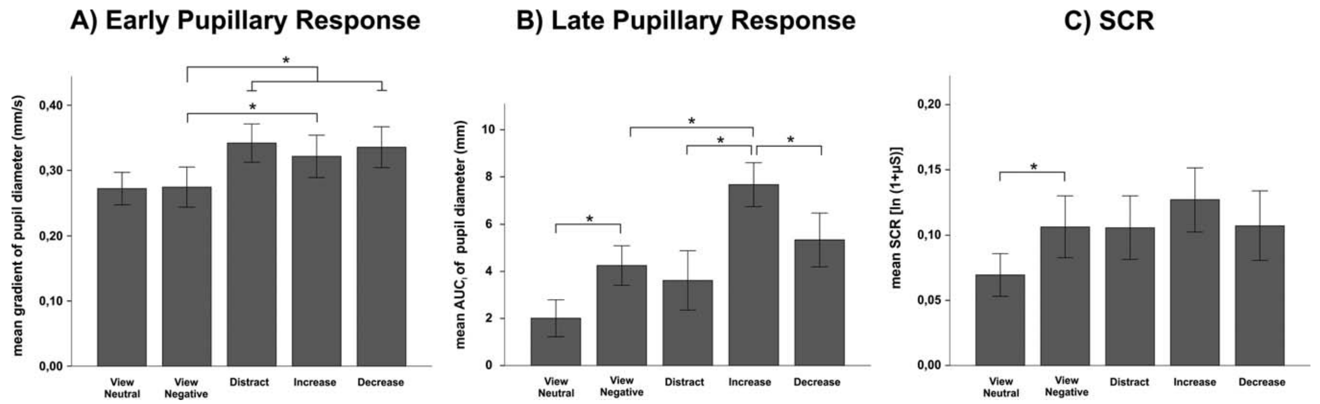

Figure 5. Mean (± *SEM*) Early pupillary responses, late pupillary responses, and skin conductance responses (SCRs) to neutral and negative pictures in the view condition and the three different emotion regulation conditions (distract, increase, decrease). A: Early pupillary dilation (indexed by a gradient) was significantly greater in all regulation conditions when compared to the view negative condition. Pupil size did not differ between viewing neutral and negative pictures. B: Late pupil dilation (determined as the area under the curve with respect to increase [AUC_I]) was significantly greater when viewing negative pictures compared to neutral pictures. Moreover, increasing emotional responses toward negative pictures resulted in the largest pupil diameter compared to all other conditions. C: SCRs were significantly higher to negative pictures than to neutral pictures in the view condition. However, in contrast to pupillary responses, SCRs were not further modulated by emotion regulation processes. *$p < .033$; $p < .0167$ (Bonferroni-corrected planned comparisons or post hoc *t* tests, respectively).

instructional cue was delivered after emotional picture onset (Urry et al., 2006, 2009; van Reekum et al., 2007). Alternatively, the early cognitive amplification of pupil sizes may also derive from temporal features of the emotion regulation strategies. Distraction and cognitive reappraisal are both so-called antecedent-focused strategies that are applied before an emotion has completely unfolded (Gross, 1998a). They thereby intervene relatively early in the emotion-generative process and may directly alter physiological response tendencies (Gross, 1998b,). In line with this notion, it has been shown that individuals habitually using reappraisal display larger pupil sizes during the anticipation of emotional stimuli (Vanderhasselt et al., 2014). Together with these findings, our results therefore indicate that early peak dilations in particular reflect emotion regulation effort.

In contrast, late pupillary responses were differentially affected by the respective emotion regulation strategies. For the AUC_I measure, the most prominent pupil size enlargements were found in the increase condition, indicative of a successful upregulation of negative emotions as also reflected in the subjective ratings. Consistent with this, cognitive reappraisal has repeatedly been shown to effectively enhance or reduce autonomic measures of arousal such as startle eyeblink, SCRs (Eippert et al., 2007; Feeser et al., 2014) and facial corrugator electromyographic responses (Kim & Hamann, 2012). Our results expand these findings, showing that upregulated emotional arousal is also expressed in pupil size increases that predominantly occur late within the pupillary response curve. Along with the late pupil size amplification observed during negative picture viewing, these effects suggest that late pupillary responses not only vary as a function of pure emotional arousal but are furthermore related to the extent one is able to exert control over these automatic processes, thereby reflecting emotion regulation outcome.

However, it must be acknowledged that attempts to downregulate negative emotions did not result in significantly smaller pupil sizes. For distraction, pupil diameter was slightly reduced compared to the negative view condition, but this effect did not reach significance. In contrast, when decreasing negative emotions through reappraisal, pupil size even tended to increase during the late time interval. Similar to these results, a number of studies using brain imaging or peripheral physiological measures of arousal demonstrated consistent effects of emotional upregulation, but failed to show an attenuating effect of downregulation (Eippert et al., 2007; Urry et al., 2006). Congruently, pupil diameter has also previously been shown to be amplified by both increasing and decreasing negative emotions (Urry et al., 2009). Interestingly, a study by Stanners, Coulter, Sweet, and Murphy (1979) revealed that the pupil only dilated in response to emotional arousal when cognitive task demands were kept minimal. These findings suggest that cognitive processes might dominate over emotional processes in controlling the pupillary response during tasks that include both aspects (Chen & Epps, 2013). In the present study, it is therefore conceivable that the decreased emotional arousal, which should manifest in the late component, was buffered by sustained early dilations caused by the downregulating effort. The absence of a modulation of the AUC_I measure in the distract and decrease conditions might thus in part be the result of opposing early cognitive and late emotional effects canceling each other out.

In line with this assumption, the AUC_G, serving as a summary measure of total pupil diameter increase, was found to be amplified in all regulation conditions, with most prominent pupil diameter changes in the distract condition. Similar results have been reported in previous emotion regulation studies using overall measures for total pupil diameter change (Urry et al., 2006, 2009; van Reekum et al., 2007). Together with these findings, our results suggest that summary measures such as the AUC_G rather depict a combination of cognitive and emotional effects and not emotion regulation success per se. Contrary to that, the AUC_I selectively captures only late pupillary responses that might be less confounded by early cognitive regulation processes, and therefore provide important additional information on pupillary response dynamics that could not be assessed with overall measures of total pupil diameter change. Thus, future studies should take into account that emotion regulation effects may considerably differ depending on the prevailing approach to analyzing pupil dilation. The differences between AUC_I and AUC_G in the present study, moreover, emphasize that baseline values that serve as a reference for emotional or regulated emotional responses should be selected carefully.

Altogether, we believe that pupillometric data revealed a specific temporal response pattern suitable to dissect emotion regulation effort from emotion regulation outcome.

Interestingly, in contrast to pupillary responses, SCRs were only affected by picture emotionality but not further modulated by the different emotion regulation strategies. These results converge with previous studies reporting no effects of emotion regulation on SCRs (Dunn et al., 2009; Kalisch et al., 2005). Nevertheless, there is also work demonstrating that SCRs could be enhanced or reduced according to a specific regulatory goal (Feeser et al., 2014; Kim & Hamann, 2012; Matejka et al., 2013; Urry et al., 2009). If pupil dilation and SCRs both index sympathetic arousal, it thus remains unclear why these measures somewhat diverged specifically during emotion regulation processes in the current study. Evidence from neurophysiological recordings in monkeys has revealed that pupil diameter correlates remarkably well with activity in the locus coeruleus (LC; Rajkowski, Kubiak, & Aston-Jones, 1993), suggesting that the pupil is not only innervated by the sympathetic branch but also by central LC neurons (Aston-Jones & Cohen, 2005). Since phasic LC activation is proposed to promote task engagement and facilitate ensuing behaviors (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Murphy, Robertson, Balsters, & O'Connell, 2011), it is therefore plausible that the pupillary response is more sensitive depicting different emotion regulatory states that individuals are cognitively engaged in. In contrast, the SCR is driven by sympathetic changes and has primarily been used to assess distinct physiological fear responses (Sehlmeyer et al., 2009; Vervliet, Baeyens, Van den Bergh, & Hermans, 2013). Moreover, SCRs are known to be sensitive to habituation (Vervliet et al., 2013). Since all regulation conditions in the present task involved some degree of emotional activation initially induced by the presentation of negative pictures, it is therefore conceivable that subtle changes in arousal initiated by the different emotion regulation strategies could not be reliably tracked by SCRs. Alternatively, regulation-induced alterations in SCRs could have occurred with a longer delay that was not detectable within the current analysis window. While the pupil responds almost immediately at stimulus onset, changes in SCR evolve slightly delayed and relatively slowly with a gradual recovery to baseline (Nieuwenhuis et al., 2011). Longer intervals between consecutive trials might help to better delineate SCRs that actually occur in response to two successively presented stimuli. Future studies are needed to directly address this possibility. Moreover, only female participants were included in the present study, which potentially limits the generalizability of our results. Since emotional reactivity and emotion processing have been shown to differ between men and women (Bradley et al., 2001; Canli et al., 2002; Lithari et al., 2010), future experiments should investigate potential sex differences in emotion regulation.

In conclusion, our findings demonstrate that both cognitive and emotional processes involved in emotion regulation are expressed in the pupillary response. Furthermore, the current data provide first evidence that the pupillary response can be subdivided into two distinct temporal components that reflect emotion regulation effort on the one hand and emotion regulation success on the other hand. Therefore, the pupil constitutes a suitable novel tool to investigate different emotion regulation strategies, in particular with regard to their efficacy in altering psychophysiological response tendencies in emotion. Mixed effects concerning the downregulation of negative emotions, however, emphasized the demand for more studies including multiple indicators of autonomic arousal to better delineate the contributions of emotional arousal and cognitive demand. Such studies may foster our understanding of the basic psychological and physiological mechanisms involved in emotion regulation and may further help to dissect whether certain strategies are more adaptive than others.

References

Andreassi, J. L. (2000). Pupillary response and behavior. In J. L. Andreassi (Ed.), *Psychophysiology: Human behavior & physiological response* (pp. 218–233): Mahwah, NJ: Lawrence Erlbaum Associates.

Aston-Jones, G., & Cohen, J. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*, 403–450. doi: 10.1146/annurev.neuro.28.061604.135709

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin*, *91*, 276–292. doi: 10.1037/0033-2909.91.2.276

Beatty, J. (1986). The pupillary system. In G. H. Coles, E. Donchin, & S. W. Porges (Eds.), *Psychophysiology: Systems, process, and applications* (pp. 43–50). New York, NY: Guilford Press.

Beatty, J., & Kahneman, D. (1966). Pupillary changes in two memory tasks. *Psychonomic Science*, *5*, 371–372. doi: 10.3758/BF03328444

Beatty, J., & Lucero-Wagoner, B. (2000). The pupillary system. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology* (pp. 142–162). Cambridge, England: University Press.

Bebko, G. M., Franconeri, S. L., Ochsner, K. N., & Chiao, J. Y. (2011). Look before you regulate: Differential perceptual strategies underlying expressive suppression and cognitive reappraisal. *Emotion*, *11*, 732–742. doi: 10.1037/a0024009

Bebko, G. M., Franconeri, S. L., Ochsner, K. N., & Chiao, J. Y. (2014). Attentional deployment is not necessary for successful emotion regulation via cognitive reappraisal or expressive suppression. *Emotion*, *14*, 504–512. doi: 10.1037/a0035459

Bradley, M. M., Codispoti, M., Sabatinelli, D., & Lang, P. J. (2001). Emotion and motivation II: Sex differences in picture processing. *Emotion*, *1*, 300–319. doi: 10.1037/1528-3542.1.3.300

Bradley, M. M., Miccoli, L., Escrig, M. A., & Lang, P. J. (2008). The pupil as a measure of emotional arousal and autonomic activation. *Psychophysiology*, *45*, 602–607. doi: 10.1111/j.1469-8986.2008.00654.x

Braver, S. L., MacKinnon, D. P., & Page, M. (2003). *Levine's guide to SPSS for analysis of variance*. Hove, UK: Psychology Press.

Buhle, J. T., Silvers, J. A., Wager, T. D., Lopez, R., Onyemekwu, C., Kober, H., . . ., Ochsner, K. N. (2014). Cognitive reappraisal of emotion: A meta-analysis of human neuroimaging studies. *Cerebral Cortex*, *24*, 2981–2990. doi: 10.1093/cercor/bht154

Canli, T., Desmond, J. E., Zhao, Z., & Gabrieli, J. D. (2002). Sex differences in the neural basis of emotional memories. *Proceedings of the National Academy of Sciences*, *99*, 10789–10794. doi: 10.1073/pnas.162356599

Chen, S., & Epps, J. (2013). Automatic classification of eye activity for cognitive load measurement with emotion interference. *Computer Methods and Programs in Biomedicine*, *110*, 111–124. doi: 10.1016/j.cmpb.2012.10.021

Dorfel, D., Lamke, J. P., Hummel, F., Wagner, U., Erk, S., & Walter, H. (2014). Common and differential neural networks of emotion regulation by detachment, reinterpretation, distraction, and expressive suppression: A comparative fMRI investigation. *NeuroImage*, *101*, 298–309. doi: 10.1016/j.neuroimage.2014.06.051

Driscoll, D., Tranel, D., & Anderson, S. W. (2009). The effects of voluntary regulation of positive and negative emotion on psychophysiological responsiveness. *International Journal of Psychophysiology*, *72*, 61–66. doi: 10.1016/j.ijpsycho.2008.03.012

Dunn, B. D., Billotti, D., Murphy, V., & Dalgleish, T. (2009). The consequences of effortful emotion regulation when processing distressing material: A comparison of suppression and acceptance. *Behaviour Research and Therapy*, *47*, 761–773. doi: 10.1016/j.brat.2009.05.007

Eftekhari, A., Zoellner, L. A., & Vigil, S. A. (2009). Patterns of emotion regulation and psychopathology. *Anxiety, Stress and Coping*, *22*, 571–586. doi: 10.1080/10615800802179860

Eippert, F., Veit, R., Weiskopf, N., Erb, M., Birbaumer, N., & Anders, S. (2007). Regulation of emotional responses elicited by threat-related stimuli. *Human Brain Mapping*, *28*, 409–423. doi: 10.1002/hbm.20291

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175–191. doi: 10.3758/BF03193146

Feeser, M., Prehn, K., Kazzer, P., Mungee, A., & Bajbouj, M. (2014). Transcranial direct current stimulation enhances cognitive control during emotion regulation. *Brain Stimulation*, *7*, 105–112. doi: 10.1016/j.brs.2013.08.006

Gilzenrat, M. S., Nieuwenhuis, S., Jepma, M., & Cohen, J. D. (2010). Pupil diameter tracks changes in control state predicted by the adaptive gain theory of locus coeruleus function. *Cognitive, Affective & Behavioral Neuroscience*, *10*, 252–269. doi: 10.3758/CABN.10.2.252

Goldin, P. R., McRae, K., Ramel, W., & Gross, J. J. (2008). The neural bases of emotion regulation: Reappraisal and suppression of negative emotion. *Biological Psychiatry*, *63*, 577–586. doi: 10.1016/j.biopsych.2007.05.031

Gross, J. J. (1998a). Antecedent- and response-focused emotion regulation: Divergent consequences for experience, expression, and physiology. *Journal of Personality and Social Psychology*, *74*, 224–237. doi: 10.1037/0022-3514.74.1.224

Gross, J. J. (1998b). The emerging field of emotion regulation: An integrative review. *Review of General Psychology*, *2*, 271–299. doi: 10.1037/1089-2680.2.3.271

Gross, J. J. (2002). Emotion regulation: Affective, cognitive, and social consequences. *Psychophysiology*, *39*, 281–291. doi: 10.1017/S0048577201393198

Gross, J. J. (2015). Emotion regulation: Current status and future prospects. *Psychological Inquiry*, *26*, 1–26. doi: 10.1080/1047840X.2014.940781

Gross, J. J., & John, O. P. (2003). Individual differences in two emotion regulation processes: Implications for affect, relationships, and well-being. *Journal of Personality and Social Psychology*, *85*, 348–362. doi: 10.1037/0022-3514.85.2.348

Gross, J. J., & Levenson, R. W. (1997). Hiding feelings: The acute effects of inhibiting negative and positive emotion. *Journal of Abnormal Psychology*, *106*, 95–103. doi: 10.1037/0021-843X.106.1.95

Hager, W. (2004). *Testplanung zur statistischen Prüfung psychologischer Hypothesen: Die Ableitung von Vorhersagen und die Kontrolle der Determinanten des statistischen Tests* [Planning tests for the statistical testing of psychological hypotheses: The deduction of predictions and the control of determinants of statistical tests]. Oxford, UK: Hogrefe.

Hamacher-Dang, T. C., Merz, C. J., & Wolf, O. T. (2015). Stress following extinction learning leads to a context-dependent return of fear. *Psychophysiology*, *52*, 489–498. doi: 10.1111/psyp.12384

Henderson, R. R., Bradley, M. M., & Lang, P. J. (2014). Modulation of the initial light reflex during affective picture viewing. *Psychophysiology*, *51*, 815–818. doi: 10.1111/psyp.12236

Hess, E. H., & Polt, J. M. (1964). Pupil size in relation to mental activity during simple problem-solving. *Science*, *143*, 1190–1192. doi: 10.1126/science.143.3611.1190

Jackson, D. C., Malmstadt, J. R., Larson, C. L., & Davidson, R. J. (2000). Suppression and enhancement of emotional responses to unpleasant pictures. *Psychophysiology*, *37*, 515–522. doi: 10.1111/1469-8986.3740515

Janisse, M. P. (1974). Pupil size, affect and exposure frequency. *Social Behavior and Personality*, *2*, 125–146. doi: 10.2224/sbp.1974.2.2.125

Johnstone, T., van Reekum, C. M., Urry, H. L., Kalin, N. H., & Davidson, R. J. (2007). Failure to regulate: Counterproductive recruitment of top-down prefrontal-subcortical circuitry in major depression. *Journal of Neuroscience*, *27*, 8877–8884. doi: 10.1523/JNEUROSCI.2063-07.2007

Kalisch, R. (2009). The functional neuroanatomy of reappraisal: Time matters. *Biobehavioral Reviews*, *33*, 1215–1226. doi: 10.1016/j.neubiorev.2009.06.003

Kalisch, R., Wiech, K., Critchley, H. D., Seymour, B., O'Doherty, J. P., Oakley, . . ., Dolan, R. J. (2005). Anxiety reduction through detachment: Subjective, physiological, and neural effects. *Journal of Cognitive Neuroscience*, *17*, 874–883. doi: 10.1162/0898929054021184

Kanske, P., Heissler, J., Schonfelder, S., Bongers, A., & Wessa, M. (2011). How to regulate emotion? Neural networks for reappraisal and distraction. *Cerebral Cortex*, *21*, 1379–1388. doi: 10.1093/cercor/bhq216

Khalfa, S., Isabelle, P., Jean-Pierre, B., & Manon, R. (2002). Event-related skin conductance responses to musical emotions in humans. *Neuroscience Letters*, *328*, 145–149. doi: 10.1016/S0304-3940(02)00462-7

Kim, S. H., & Hamann, S. (2012). The effect of cognitive reappraisal on physiological reactivity and emotional memory. *International Journal of Psychophysiology*, *83*, 348–356. doi: 10.1016/j.ijpsycho.2011.12.001

Kinner, V. L., Het, S., & Wolf, O. T. (2014). Emotion regulation: Exploring the impact of stress and sex. *Frontiers in Behavioral Neuroscience*, *8*, 397. doi: 10.3389/fnbeh.2014.00397

Kret, M. E., Roelofs, K., Stekelenburg, J., & de Gelder, B. (2013). Salient cues from faces, bodies and scenes influence observers' face expressions, fixations and pupil size. *Frontiers in Human Neuroscience*, *7*. doi: 10.3389/fnhum.2013.00810

Kuchinke, L., Schneider, D., Kotz, S. A., & Jacobs, A. M. (2011). Spontaneous but not explicit processing of positive sentences impaired in Asperger's syndrome: Pupillometric evidence. *Neuropsychologia*, *49*, 331–338. doi: 10.1016/j.neuropsychologia.2010.12.026

Kuchinke, L., Vo, M. L., Hofmann, M., & Jacobs, A. M. (2007). Pupillary responses during lexical decisions vary with word frequency but not emotional valence. *International Journal of Psychophysiology*, *65*, 132–140. doi: 10.1016/j.ijpsycho.2007.04.004

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (2008). *International affective picture system (IAPS): Affective ratings of pictures and instruction manual*. Technical Report A-8. University of Florida, Gainesville, FL.

Lang, P. J., Greenwald, M. K., Bradley, M. M., & Hamm, A. O. (1993). Looking at pictures: Affective, facial, visceral, and behavioral reactions. *Psychophysiology*, *30*, 261–273. doi: 10.1111/j.1469-8986.1993.tb03352.x

Lithari, C., Frantzidis, C. A., Papadelis, C., Vivas, A. B., Klados, M. A., Kourtidou-Papadeli, C., . . ., Bamidis, P. D. (2010). Are females more responsive to emotional stimuli? A neurophysiological study across arousal and valence dimensions. *Brain Topography*, *23*, 27–40. doi: 10.1007/s10548-009-0130-5

Loewenstein, O., & Loewenfeld, I. E. (1962). The pupil. In H. Davson (Ed.), *The eye. Vol 3. Muscular mechanisms*. New York, NY: Academic Press.

Matejka, M., Kazzer, P., Seehausen, M., Bajbouj, M., Klann-Delius, G., Menninghaus, W., . . ., Prehn, K. (2013). Talking about emotion: Prosody and skin conductance indicate emotion regulation. *Frontiers in Psychology*, *4*, 260. doi: 10.3389/fpsyg.2013.00260

McRae, K., Hughes, B., Chopra, S., Gabrieli, J. D., Gross, J. J., & Ochsner, K. N. (2010). The neural bases of distraction and reappraisal. *Journal of Cognitive Neuroscience*, *22*, 248–262. doi: 10.1162/jocn.2009.21243

Meir Drexler, S., Merz, C. J., Hamacher-Dang, T. C., Tegenthoff, M., & Wolf, O. T. (2015). Effects of cortisol on reconsolidation of reactivated fear memories. *Neuropsychopharmacology*, *40*, 3036–3043. doi: 10.1038/npp.2015.160

Merz, C. J., Hamacher-Dang, T. C., & Wolf, O. T. (2014). Exposure to stress attenuates fear retrieval in healthy men. *Psychoneuroendocrinology*, *41*, 89–96. doi: 10.1016/j.psyneuen.2013.12.009

Moresi, S., Adam, J. J., Rijcken, J., Van Gerven, P. W., Kuipers, H., & Jolles, J. (2008). Pupil dilation in response preparation. *International Journal of Psychophysiology*, *67*, 124–130. doi: 10.1016/j.ijpsycho.2007.10.011

Murphy, P. R., Robertson, I. H., Balsters, J. H., & O'Connell, R. G. (2011). Pupillometry and P3 index the locus coeruleus-noradrenergic arousal function in humans. *Psychophysiology*, *48*, 1532–1543. doi: 10.1111/j.1469-8986.2011.01226.x

Nieuwenhuis, S., De Geus, E. J., & Aston-Jones, G. (2011). The anatomical and functional relationship between the P3 and autonomic components of the orienting response. *Psychophysiology*, *48*, 162–175. doi: 10.1111/j.1469-8986.2010.01057.x

Ochsner, K. N., Bunge, S. A., Gross, J. J., & Gabrieli, J. D. (2002). Rethinking feelings: An fMRI study of the cognitive regulation of emotion. *Journal of Cognitive Neuroscience*, *14*, 1215–1229. doi: 10.1162/089892902760807212

Ochsner, K. N., & Gross, J. J. (2005). The cognitive control of emotion. *Trends in Cognitive Sciences*, *9*, 242–249. doi: 10.1016/j.tics.2005.03.010

Partala, T., & Surakka, V. (2003). Pupil size variation as an indication of affective processing. *International Journal of Human-Computer Studies*, *59*, 185–198. doi: 10.1016/S1071-5819(03)00017-X

Prehn, K., Heekeren, H. R., Blasek, K., Lapschies, K., Mews, I., & van der Meer, E. (2008). Neuroticism influences pupillary responses during an emotional interference task. *International Journal of Psychophysiology*, *70*, 40–49. doi: 10.1016/j.ijpsycho.2008.04.006

Prehn, K., Heekeren, H. R., & van der Meer, E. (2011). Influence of affective significance on different levels of processing using pupil dilation in an analogical reasoning task. *International Journal of Psychophysiology*, *79*, 236–243. doi: 10.1016/j.ijpsycho.2010.10.014

Pruessner, J. C., Kirschbaum, C., Meinlschmid, G., & Hellhammer, D. H. (2003). Two formulas for computation of the area under the curve represent measures of total hormone concentration versus time-dependent change. *Psychoneuroendocrinology*, *28*, 916–931. doi: 10.1016/S0306-4530(02)00108-7

Rajkowski, J., Kubiak, P., & Aston-Jones, G. (1993). Correlations between locus coeruleus (LC) neural activity, pupil diameter and behavior in monkey support a role of LC in attention [Abstract]. *Society of Neuroscience Abstracts*, *19*.

Ray, R. D., McRae, K., Ochsner, K. N., & Gross, J. (2010). Cognitive reappraisal of negative affect: Converging evidence from EMG and self-report. *Emotion*, *10*, 587–592. doi: 10.1037/a0019015

Richey, J. A., Damiano, C. R., Sabatino, A., Rittenberg, A., Petty, C., Bizzell, J., . . ., Dichter, G. S. (2015). Neural mechanisms of emotion regulation in autism spectrum disorder. *Journal of Autism and Developmental Disorders*, *45*, 3409–3423. doi: 10.1007/s10803-015-2359-z

Schiller, D., Cain, C. K., Curley, N. G., Schwartz, J. S., Stern, S. A., LeDoux, J. E., & Phelps, E. A. (2008). Evidence for recovery of fear following immediate extinction in rats and humans. *Learning & Memory*, *15*, 394–402. doi: 10.1101/lm.909208

Schiller, D., Kanen, J. W., LeDoux, J. E., Monfils, M.-H., & Phelps, E. A. (2013). Extinction during reconsolidation of threat memory diminishes prefrontal cortex involvement. *Proceedings of the National Academy of Sciences*, *110*, 20040–20045. doi: 10.1073/pnas.1320322110

Sehlmeyer, C., Schoning, S., Zwitserlood, P., Pfleiderer, B., Kircher, T., Arolt, V., & Konrad, C. (2009). Human fear conditioning and extinction in neuroimaging: A systematic review. *PLOS ONE*, *4*, e5865. doi: 10.1371/journal.pone.0005865

Sheppes, G., Catran, E., & Meiran, N. (2009). Reappraisal (but not distraction) is going to make you sweat: Physiological evidence for self-control effort. *International Journal of Psychophysiology*, *71*, 91–96. doi: 10.1016/j.ijpsycho.2008.06.006

Sheppes, G., Suri, G., & Gross, J. J. (2015). Emotion regulation and psychopathology. *Annual Review of Clinical Psychology*, *11*, 379–405. doi: 10.1146/annurev-clinpsy-032814-112739

Sirois, S., & Brisson, J. (2014). Pupillometry. *Wiley Interdisciplinary Reviews: Cognitive Science*, *5*, 679–692. doi: 10.1002/wcs.1323

Stanners, R. F., Coulter, M., Sweet, A. W., & Murphy, P. (1979). The pupillary response as an indicator of arousal and cognition. *Motivation and Emotion*, *3*, 319–340. doi: 10.1007/BF00994048

Urry, H. L. (2009). Using reappraisal to regulate unpleasant emotional episodes: Goals and timing matter. *Emotion*, *9*, 782–797. doi: 10.1037/a0017109

Urry, H. L. (2010). Seeing, thinking, and feeling: Emotion-regulating effects of gaze-directed cognitive reappraisal. *Emotion*, *10*, 125–135. doi: 10.1037/a0017434

Urry, H. L., van Reekum, C. M., Johnstone, T., & Davidson, R. J. (2009). Individual differences in some (but not all) medial prefrontal regions reflect cognitive demand while regulating unpleasant emotion. *NeuroImage*, *47*, 852–863. doi: 10.1016/j.neuroimage.2009.05.069

Urry, H. L., van Reekum, C. M., Johnstone, T., Kalin, N. H., Thurow, M. E., Schaefer, H. S., . . ., Davidson, R. J. (2006). Amygdala and ventromedial prefrontal cortex are inversely coupled during regulation of negative affect and predict the diurnal pattern of cortisol secretion among older adults. *Journal of Neuroscience*, *26*, 4415–4425. doi: 10.1523/JNEUROSCI.3215-05.2006

Van Dillen, L. F., & Koole, S. L. (2007). Clearing the mind: A working memory model of distraction from negative mood. *Emotion*, *7*, 715–723. doi: 10.1037/1528-3542.7.4.715

van Reekum, C. M., Johnstone, T., Urry, H. L., Thurow, M. E., Schaefer, H. S., Alexander, A. L., & Davidson, R. J. (2007). Gaze fixations predict brain activation during the voluntary regulation of picture-induced negative affect. *NeuroImage*, *36*, 1041–1055. doi: 10.1016/j.neuroimage.2007.03.052

Vanderhasselt, M.-A., Remue, J., Ng, K. K., & De Raedt, R. (2014). The interplay between the anticipation and subsequent online processing of emotional stimuli as measured by pupillary dilatation: The role of cognitive reappraisal. *Frontiers in Psychology*, *5*. doi: 10.3389/fpsyg.2014.00207

Vervliet, B., Baeyens, F., Van den Bergh, O., & Hermans, D. (2013). Extinction, generalization, and return of fear: A critical review of renewal research in humans. *Biological Psychology*, *92*, 51–58. doi: 10.1016/j.biopsycho.2012.01.006

Vujovic, L., Opitz, P. C., Birk, J. L., & Urry, H. L. (2014). Cut! that's a wrap: Regulating negative emotion by ending emotion-eliciting situations. *Frontiers in Psychology*, *5*, 165. doi: 10.3389/fpsyg.2014.00165

Willenbockel, V., Sadr, J., Fiset, D., Horne, G. O., Gosselin, F., & Tanaka, J. W. (2010). Controlling low-level image properties: The SHINE toolbox. *Behavioral Research Methods*, *42*, 671–684. doi: 10.3758/BRM.42.3.671

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