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Attachment is in the eye of the beholder: a pupillometry study on emotion processing

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Early attachment relationships exert lasting effects on psychophysical health across the lifespan. Limited behavioral evidence suggests that these effects stem from how individuals perceive, interpret, and respond to their environment. This study investigated whether adults' attachment representations modulate autonomic responses to happy and sad facial expressions, evidenced by changes in pupil size. We utilized a sample of healthy adults (*N* = 100; 68% females, 18–35 years, prevalently White European). In an eye-tracking experiment, we assessed pupil dilation to happy and sad facial expressions (*n* = 152 trials). Dismissing and preoccupied attachment orientations were assessed as continuous dimensions via self-report. Linear mixed models revealed that individuals with higher scores on dismissing orientations exhibited a significant increase in pupil dilation in response to sad and not happy expressions. No significant effects were observed for preoccupied orientations, age, or sex. These findings suggest that individuals with increased scores on dismissing attachment show heightened arousal to negative emotions.

Keywords Attachment theory, Pupillometry, Autonomic nervous system, Emotion regulation

Attachment strategies from infancy to adulthood

Attachment relationships, conceived of as a secure base relationship between an infant and their primary caregivers[1,2], help regulate infants' psychophysiological systems and influence how they perceive, interpret, and respond to the surrounding environment[3,4]. From the first moments of life, newborns rely on their caregivers to support their psychophysical homeostasis and help them respond to and recover from environmental stressors[5,6]. Bootstrapping from these early experiences, infants construct internal cognitive scripts encoding expectations of seeking and receiving consistent and sensitive support (or not)[7–9]. Different patterns of attachment and behavioral strategies have been theorized and empirically identified based on the quality and consistency of early caregiving[10–12]. Secure attachment is characterized by the effective use of a primary caregiver as a secure base during exploration and as a haven of safety and comfort during distress. The associated confidence in their caregivers' availability is thought to arise from consistent and supportive care provided by the attachment Figs[10,13]. In contrast, a history of unsupportive care results in two distinct attachment styles indicative of attachment insecurity: dismissing and preoccupied. The dismissing strategy sees the withdrawal from intimate relationships and suppressed response to distress possibly as a protection mechanism of not having their expectations of support fail. In contrast, a preoccupied strategy features clingy and anxious behaviors, possibly underlying incessant attempts to engage with the attachment figure but receiving little immediate comfort when support is provided, as evidenced in studies entailing laboratory procedures of parent-child separation[14]. Beyond the early developmental context, such strategies are also documented in attachment instruments devised for adults, namely the Adult Attachment Interview (AAI)[15,16], wherein adults classified as dismissing use deactivating strategies that emerge as a way to suppress attachment-relevant autobiographical memories, whereas preoccupied individuals are documented to reflect anger and hyperactivating strategies in the way they discuss their attachment history. Although there is substantial indirect evidence of these behavioral strategies via narrative behavior, biologically based and experimentally controlled evidence is needed to elucidate the physiological regulatory processes underlying hyper/de-activating strategies, advancing our theoretical understanding of developmental processes and informing clinical work. Accordingly, capitalizing on these distinct behavioral strategies and the enduring impact of the early caregiving environment on later attachment orientations in adult (romantic) relationships[17] and socioemotional and cognitive development[18,19], we propose that distinct insecure attachment orientations in adulthood feature different appraisals of the surrounding environment, likely shaped by individuals' experiences

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with and expectations for a (un)safe environment, which in turn informs behavioral strategies in response to perceived threats and stressors.

Attachment and the autonomic nervous system

One of the most striking neurobiological findings regarding attachment responses to a stressor is the relation between overt behavioral strategies and covert autonomic nervous system (ANS) reactivity. Pioneering work by Dozier and Kobak[20]), later replicated by Roisman and colleagues[21], revealed that adults' hyperactivating and deactivating strategies to manage an internal stressor (i.e., recollecting negative attachment-related autobiographical memories;[14]) translate to distinct physiological reactions. Deactivating strategies during the AAI were coupled with heightened skin conductance, reflecting increased sympathetic activity, one branch of the ANS[22,23]. Although heightened electrodermal activity signals an increase in individuals' preparation for action in response to a perceived threat[24], dismissing individuals manifest heightened physiological but dampened behavioral reactions[20,21]. This result has been explained through the lens of the biological basis of personality theory postulating the Behavioral Inhibition System[25], wherein the electrodermal activity is a physiological marker of effortful inhibition to suppress negative emotion processing. Accordingly, the milder the behavioral reaction, the more strain is exerted on the sympathetic system. Furthermore, surprisingly, preoccupied individuals, featuring hyperactivating behavioral strategies during the interview did not evidence greater sympathetic activity, suggesting that behavioral hyperactivation is not linked to higher sympathetic physiological arousal. Parallel evidence in infants exposed to maternal separation and reunion episodes during the well-established laboratory Strange Situation Procedure[14] has documented a misalignment between the behavioral manifestations and underlying physiological signatures of stress. In other words, infants manifesting less fussing (i.e., deactivating strategies) had heightened saliva cortisol concentrations (thought of as the stress hormone with rapid production increase in response to acute stressors; e.g.[26], of securely attached infants[27]. Altogether, these findings reveal the intriguing neurobiological mechanisms underlying attachment strategies in an attachment context. Given that such mechanisms and strategies are known to impact individuals' social development[28], an important question arises: how do these stress regulatory mechanisms underlying attachment orientations shape individuals' interpretations and responses to their socioemotional environment, beyond the attachment context? This study sought to answer this question by assessing whether adults' hyperactivating and deactivating strategies rooted in early attachment experiences modulate sympathetic activation to positive and negative socioemotional cues. Building on a rich body of behavioral research (e.g., reaction time tasks[29]; dot-probe tasks[30]) and neuroimaging studies (e.g., fMRI[31]; psychophysiology[3]), which have revealed distinct psychobiological emotion processing across individuals with different attachment orientations, a promising new avenue of research emerges. Pupillometry, offering a noninvasive and easily accessible measure of brain activity and autonomic processes[22,32], holds great potential for providing unique insights into attachment dynamics. This technique has already made substantial contributions to the study of social cognition across the lifespan[33,34], in both typical and atypical populations[35,36]. Given that attachment theory suggests that individuals develop cognitive scripts[9] about their social world that shape their expectations and cognitive biases in future interactions, it is surprising that so little research has explored the potential of pupillometry to further our understanding of attachment processes.

Pupillometry: a window into autonomic regulation

The human eye, particularly pupillary activity, provides invaluable insights into individuals' implicit cognitive and emotional processes[37]. According to the psychophysiological model of cognitive effort[38], changes in pupil diameters reflect general physiological arousal and, specifically, how intensively the autonomic network processes emotions (e.g., pleasant vs. violent scenes;[39] and cognitive stimulation (e.g., memory tasks;[40]. Change in pupil size occurs involuntarily as a result of low-level (i.e., light reflex), mid-level (i.e., alertness), and high-level processes (i.e., executive functioning;[32]. While a full description of the neural circuits controlling pupillary activity is beyond the scope of this paper, we adopt a simplified view of the ANS here, wherein the sympathetic activity increases the activity of the dilator muscle, prompting dilation, whereas inhibition of parasympathetic activity lessens constriction of the sphincter muscle, which also results in dilation[41]. However, the close covariation of pupil dilation with skin conductance documented in prior work[42,43] suggests that, for emotional processing, pupil dilation involves direct sympathetic innervation of the dilator muscle[22]. Changes in the pupil are modulated by emotional arousal, with a larger increase in size when viewing unpleasant versus pleasant stimuli, which were also directly aligned with heightened electrodermal responses (see also[44,45]. Despite the growing literature linking attachment and psychophysiology, the modulation of attachment strategies on sympathetic pupillary activity in response to socioemotional stimuli remains unknown. The only study to our knowledge that has investigated attachment orientations and pupil dilation[46] did not find a significant relation between pupil dilation to negatively charged stimuli and adult attachment. Yet, given the modest sample size ($N = 37$) and the nature of the stimuli chosen (i.e., erotica, violence, nature), these results remain inconclusive concerning basic emotion processing modulated by attachment orientations.

Current study

The current study built on prior work linking individual differences in attachment to psychophysiology and emotion regulation and investigated the modulation of sympathetic activity indexed in pupillary responses to socioemotional cues by adult attachment. Based on prior converging evidence on heightened sympathetic activity, indexed by electrodermal activity, in dismissing individuals recollecting negative attachment experiences[20,21], we hypothesized that individuals with higher dismissing attachment scores, as a proxy for stronger deactivating strategies, would display an increase in sympathetic pupil dilation to negative stimuli compared to individuals with lower dismissing scores. This would substantiate prior findings that deactivating strategies in individuals with dismissing attachment orientation are coupled with increased sympathetic activity in an effort to down-regulate negative emotional experiences. Furthermore, by extending the investigation beyond the attachment context, these findings may provide evidence for generalized autonomic regulatory processes modulated by early attachment experiences to the larger socioemotional environment. Given that such strategies are thought to emerge under stress, we expected the effects to be specific to negative but not to positive cues. No specific hypotheses were formulated for preoccupied attachment due to limited prior research. Furthermore, although the secure dimension of attachment is undoubtedly valuable, it is beyond the scope of this study for two reasons. First, the operationalization and assessment of adult attachment in this study relies on a self-report instrument designed specifically to capture deactivating and hyperactivating strategies. Second, pupil dilation is expected to indicate higher deactivation strategies and suppression of negative emotional processing, which are characteristic of the dismissing orientation, whereas no distinct strategy is expected for the secure orientation. Lastly, we explored the effect of sex and age on the relation between attachment and pupil dilation.

Results

The linear mixed effect model for pupil dilation revealed no significant main effect of emotion on pupil size ($\beta = -0.001$, $p = 0.918$, $SE = 0.009$, 95% CI [− 0.018, 0.017]). The results revealed a small statistically significant effect of dismissing attachment scores and sad emotion on pupil size ($\beta = 0.022$, $p = 0.022$, $SE = 0.009$, 95% CI [0.004, 0.040]), and a smaller, statistically not significant effect of dismissing and happy emotion ($\beta = 0.019$, $p = 0.050$, $SE = 0.009$, 95% CI [0.001, 0.037]). These results suggest that individuals scoring higher on dismissing attachment strategies show larger increases in pupil size to negative stimuli than individuals scoring lower on dismissing attachment strategies. The effect of preoccupied attachment and sad ($\beta = 0.004$, $p = 0.496$, $SE = 0.006$, 95% CI [− 0.007, 0.015]) or happy ($\beta = 0.000$, $p = 0.996$, $SE = 0.005$, 95% CI [− 0.011, 0.011]) emotional stimuli had statistically not significant effects on pupil size increase. The effects are visualized in Fig. 1. A correlation analysis was performed between attachment orientation and baseline pupil activation to examine whether baseline pupil diameter is related to individual differences in attachment. The results revealed non-significant and trivial in magnitude correlations between happy baseline and preoccupied ($r = 0.055$, $p > 0.05$), happy baseline and dismissing ($r = 0.082$, $p > 0.05$), sad baseline and preoccupied ($r = 0.028$, $p > 0.05$), and sad baseline and dismissing ($r = 0.084$, $p > 0.05$).

Discussion

There is abundant evidence supporting the notion of distinct physiological activity in the autonomic nervous system or the hypothalamic-pituitary-adrenocortical axis underlying attachment strategies in infants and adults[21,27]. While these have been documented to occur during attachment-specific challenges, in the current study we extended the investigation to test whether a similar modulation of the autonomic process by attachment

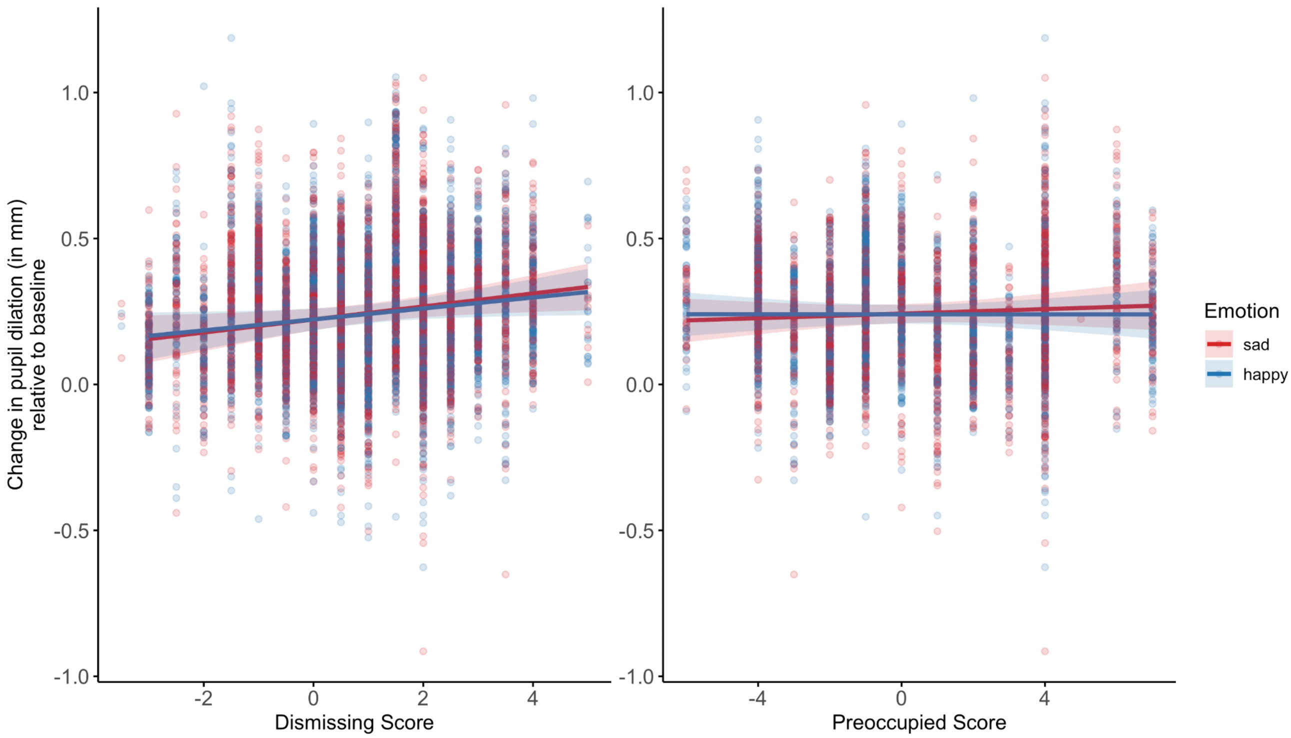

Fig. 1. Pupil responses and attachment strategies. Illustration of the pupil size increase in response to sad and happy stimuli as a function of attachment strategies. Red features increase in the pupil (in mm) to sad emotional stimuli, whereas blue to happy. The shading reflects the confidence band around the regression lines.

styles is evident to negative stimuli outside the attachment context. To do so, we utilized a large sample in an experimental study of pupillometry, as an index of sympathetic activation. Building on prior converging evidence in infants and adults that a dismissing attachment orientation manifests in a behavioral deactivating strategy that is coupled with increased physiological arousal, our study shows that individuals with a higher dismissing orientation respond with larger pupil size increase to stills of negative emotional facial expressions in a lab experiment.

The misalignment between behavioral inhibition in the attachment context and the increase in the autonomic sympathetic nervous system (i.e., electrodermal activity-EDA)[20,21] has been interpreted as a suppressive effort, so an attempt to down-regulate the negative emotion related to early attachment experiences. Our findings that individuals who report higher dismissing orientation show similar sympathetic activation, as indicated by an increase in pupil size, when confronted with negative facial expressions strengthen the notion that early attachment experiences modulate how individuals regulate negative emotions. Our study thus replicates earlier findings examining a different channel of the sympathetic nervous system, namely pupillometry. It extends current knowledge by providing evidence that such processes generalize beyond attachment relationships to other, more general socioemotional contexts. Despite the well-established link between the quality of early attachment relationships and later social adjustment[19], the mechanisms underlying these effects are still poorly understood, with some studies proposing sensory over-responsivity[47] and emotion (dys-)regulation[48] as mediators. Our findings provide initial physiological evidence that one possible mechanism through which early attachment has an enduring effect on individuals' psychological[17,49] could be through physiological profiles, namely hyperactivation of the sympathetic nervous system, established in the earliest caregiving interactions which are activated during times of distress. Given the small effect size of dismissing orientation on pupil size responses to sad emotions, caution is warranted in the interpretation of our findings. Further studies are necessary to substantiate the links between attachment and emotion processing. In line with methodological considerations in pupillometry research[22,67], we examined whether baseline pupil size during fixation periods was associated with attachment orientations. Our analyses revealed no significant correlations between baseline pupil diameter and either dismissing or preoccupied attachment scores (all $rs < 0.09$, $ps > 0.05$). These findings suggest that tonic pupillary activity during baseline was not significantly related to attachment dimensions in our sample. Instead, the observed relationship between dismissing attachment and pupillary reactivity to sad facial expressions appears specific to the phasic pupil response rather than reflecting pre-existing differences in baseline pupil size. This strengthens our interpretation that the sympathetic activation pattern observed in individuals with dismissing attachment is specifically triggered by negative emotional stimuli, supporting the notion of distinct emotion processing mechanisms linked to attachment styles.

Attachment theory[1,2,14] posits that the attachment system becomes active when the child is in distress. Later work[20] documented that the behavioral strategies marked by insecure dismissing strategies are coupled with distinct physiological activation of the sympathetic system in the attachment context. The early developmental context thus might serve as the cradle of the developing stress-regulation system. Before birth, the mother's and the infant's biological systems are coupled, with the mother's system supporting regulation in the fetus[50]. After birth, the two stress systems become independent, posing a challenge for infant self-regulation and simultaneously demands on caregivers' co-regulation of their infants[51]. While babies are born with a well-functioning biological stress system, they must master the ability to adaptively calibrate their response to a stressor in a changing environment[52], with their stress response relying on internal (i.e., autonomic nervous system) and external regulators (i.e., caregivers). In other words, caregivers provide attuned response to the child's emotional needs and thus a foundation for infants to learn how to react and calibrate their responses to stressors[53]. Based on internalized cognitive scripts of early caregiving experiences, humans may develop and exhibit specific stress-regulation strategies featuring distinct physiological profiles. This proposition begs future investigations of the role of attachment relationships in the development of individual differences in stress regulation.

A limitation of this study concerns the use of only one physiological marker indexing the sympathetic autonomic nervous system, namely pupillometry. Recent studies[42,43] have examined multiple markers of sympathetic activity, such as EDA and pupil dilation, and found evidence of convergence in responses to emotional stimuli. Yet, incorporating EDA as an additional measure can provide further insights by addressing the limitations of pupillometry. In other words, the pupil can be affected by several aspects outside the investigation. One example is the pupil size of the facial expressions used as a stimulus. Additionally, the inherent social nature of faces may itself elicit pupil dilation (vs. non-social stimuli). While these factors are unlikely to account for the relationship between dismissing attachment and pupil dilation to sad emotional expressions, they should be considered in future research. To properly ground our findings and provide more evidence for the hypothesis of specific regulation strategies, multiple physiological markers tapping into the sympathetic and parasympathetic systems should be assessed. The body orchestrates these two systems to achieve homeostatic equilibrium, and they may react differently depending on the intrinsic characteristics of the stressor. Accordingly, identifying different activation profiles (also theorized in the Adaptive Calibration Model[54]), is imperative to further elucidate the neurobiological signatures of attachment and stress regulation. Another limitation of the study that warrants caution in the interpretation of our findings concerns the self-report measure of attachment orientations. In the developmental tradition, adult attachment has been assessed by the adult attachment interview (AAI;[55]) which claims to access an unconscious level of the early attachment representations, in contrast to self-report measures devised by social psychologists to assess conscious appraisals, beliefs, and attributions that individuals make about themselves and their relationships[56]. Even though the latter study suggests that self-report and interview assessments may tap into different aspects of attachment relationships and underlying individual differences which may operate at an unconscious level, these will have implications for behaviors[57]. Our study confirms this view, by replicating prior AAI findings[20,21] that individuals with dismissing attachment orientation show heightened electrodermal activity when discussing negative attachment experiences, paralleling the exposure to the negative facial expressions in our study. Caution in the interpretation of these findings and further replications are required utilizing a different set of stimuli. In this study, we included only female models and happy and sad facial expressions, since this study was a part of a larger project. Despite the rigorous design and a large number of trials, our findings require further replication in more ecologically valid settings. To address this, pupillometry integrated into wearable technology or virtual reality could provide new opportunities for investigating attachment-relevant contexts, such as interpersonal dynamics. Furthermore, from a procedural perspective, although the lighting level was maintained constant across participants, we did not assess it quantitatively and were unable to include this as a covariate.

Our findings concerning preoccupied and secure attachment orientations yielded no statistically significant evidence for a modulation of pupil responses, which is in line with prior research using skin conductance measures[20,21]. The specificity of the sympathetic activation for dismissing but no other attachment orientations provide supporting evidence for distinct physiological profiles for different attachment strategies. In line with this, Roisman and colleagues[21] assessed parasympathetic activity using cardiac measures and found no evidence for the implication of the parasympathetic system in regulatory processes during access to autobiographical attachment experiences. Nevertheless, the interactive involvement of the two systems remains largely unexplored and offers new opportunities for investigation. Although we found a specific interaction effect between dismissing and negative emotion, we cannot neglect that a similar trend, although not statistically significant emerged for happy emotions, precluding strong interpretations on the specificity of the response to negative emotions.

In sum, our study provides evidence that attachment orientation in adults modulates sympathetic activation to negative emotions. A stronger pupil response to negative facial expressions for individuals with higher dismissing attachment scores supports the notion that increased effortful control is recruited to down-regulate negative emotion processing in those employing deactivating, strategies.

Methods
Participants
A hundred participants with normal or corrected-to-normal vision (68 females; M_{Age} = 24.54 years, SD_{Age} = 3.90 years, range 18–35 years, primarily White European) participated in this study. The sample size was estimated with a priori power analysis (G*Power software). Data from this project have previously been used to investigate the impact of attachment on facial muscle activation and to develop and evaluate processing guidelines for electromyographic data[58,59]. A small effect size was expected for the current project, although no prior work is known on the topic. A sample of 100 participants was deemed suitable to answer the current research questions. Four participants were excluded for not meeting the minimum criteria for inclusion in the pupil responses analyses (see data processing section below). Data collection occurred in the Netherlands, where data on race/ethnicity is strictly regulated concerning storage and is not customary to be asked for if it is not part of the research question; thus, these details are not provided. Participants were recruited through the Radboud University online research registration system. Participants were compensated with €10 or one study credit. The study was approved by the ethics committee of the Faculty of Social Sciences at Radboud University, Nijmegen, in the Netherlands, and was conducted according to the ethical standards of the Declaration of Helsinki. Written informed consent was obtained from all participants before the start of the experimental procedure. The experiment lasted approximately 30 min. After the experimental procedure, the participants completed the attachment questionnaire. Lastly, they were debriefed, compensated, and thanked for their participation. The data and code to reproduce the analyses are available on GitHub. The materials are available on the Donders Repository of the Radboud University.

Design and stimulus material
Stills of nineteen White female models' facial expressions featuring happy and sad emotions were selected from the Radboud Faces Database[60]. Each stimulus was presented four times, resulting in 152 trials presented in a pseudo-randomized manner using MIX[61]. The following constraints were applied: each model could not be presented more than once consecutively, and each emotion could not be presented more than twice in a row. Each trial lasted 4000 ms and unfolded as follows: 1000 ms fixation cross, 2000 ms stimulus presentation, and a 1000-ms inter-trial interval (Fig. 2). Consequently, stimuli were presented 2000 ms apart, which falls within the typical range of 500–2500 ms for cognitive and emotion-elicitation tasks[62–64]. This timing helps to mitigate potential carryover effects of pupillary dilation. Additionally, the final interval of 1000 ms was used to statistically correct for any residual pupil response from the prior trial. With the onset of the fixation cross a brief, a short beep was played as an attention-getter. The stimuli were presented using Tobii Studio Software (3.3.0). Pupil data were recorded at 120 Hz by a corneal reflection eye tracker (Tobii TX300, Tobii Technology, Danderyd, Sweden) after calibration with a 9-point procedure. The procedure was repeated if only seven or fewer calibration points were detected. Adults were seated on a chair in front of the eye-tracker screen at a distance of 60 cm. The room was dimly lit and was constant across participants. To be able to control for potentially confounding differences in stimulus luminance across happy and sad stimuli, the relative luminance per image was calculated[65]; see Supplementary material for details). This was done by first converting the sRGB values of the image pixels to linear light values using gamma correction. In a second step, pixel-wise luminance was calculated using the coefficients 0.2126 for red, 0.7152 for green, and 0.0722 for blue. Finally, stimulus luminance was calculated by averaging over the pixel-wise luminance values[66]. A two-tailed t-test revealed that luminance values of happy ($\bar{X}$ = 0.427, SD = 0.027) and sad ($\bar{X}$ = 0.431, SD = 0.028) stimuli did not significantly differ ($t(36) = 0.36$, $p = 0.72$). Nevertheless, stimulus luminance was included as a factor in the main analysis. The experiment was programmed with Presentation software (Version 17.1, Neurobehavioral Systems, Inc., Berkeley, CA).

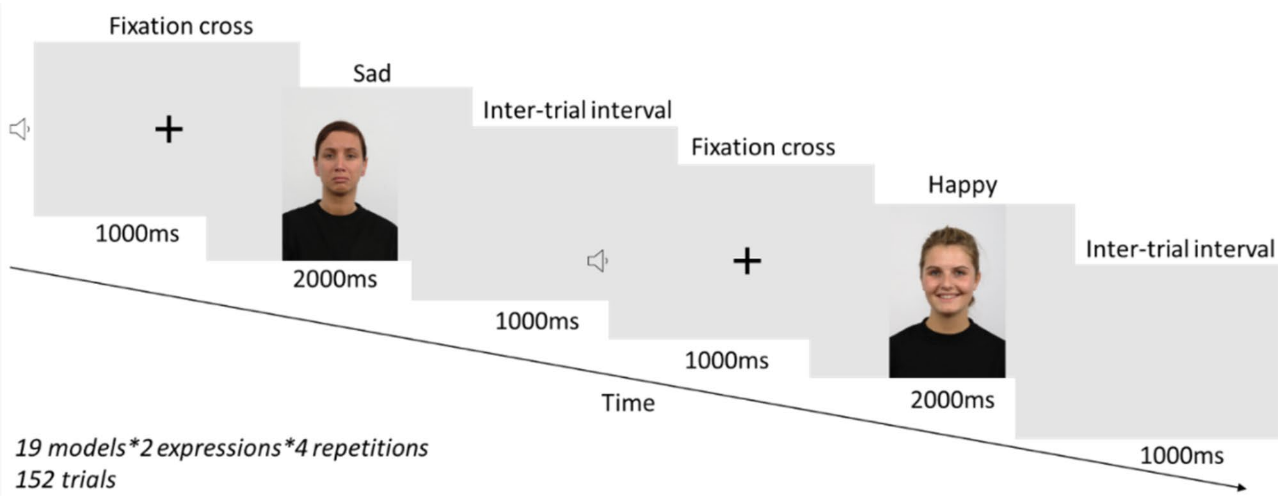

Fig. 2. Study design. Illustration of two trials featuring a happy and a sad example stimulus.

Pupillometry: data preprocessing and reduction

Data preprocessing was performed in Python following the guidelines proposed by Kret and Sjak-Shie[67]. First, the raw pupil size series for the left and right eyes were inspected and the records where the eye-tracker flagged samples as invalid in both eyes were removed. Second, pupil dilation values < 1.5 mm and > 9 mm were removed. Third, the dilation speed outliers, where the rate of change in pupil size exceeded 3 times the median absolute deviation of the rate of change were removed. Fourth, pupil dilation values of 50 ms before and after a gap of continuously missing data of > 75 ms were removed. Next, the data was segmented into a fixation (1000 ms) and stimulus period (2000 ms) per trial. After segmentation, pupil dilation values were removed if their distance to the trial-level LOWESS-smoothed trend-line was > 8 times the median absolute deviation of the trend-line distances across all trials. Next, we calculated at the trial level, the offset-corrected mean pupil size across the left and the right eye. Finally, we calculated the percentages of data points left, based on the mean pupil size, for each trial, separately for the fixation and the stimulus period. Only the trials with at least 85% data points were included in the analyses, for a total of 7516 observations (happy: 3828; sad: 3688). Five participants were excluded, three for not reaching the criterion of > 85% data points for each trial and two for not having any meaningful data left after the first four preprocessing steps. For the final analyses, 95 participants contributed an average of 79.1 trials each. To maximize the effect of the slow buildup of pupil dilation in response to the stimuli[68], we conducted the analyses on the last 500ms window (see Fig. 3).

Attachment

Attachment was assessed using the Attachment Styles Questionnaires (ASQ;[69–71]. The AQS is a self-report questionnaire assessing adults' attachment styles on four continuous dimensions, namely secure (7 items), preoccupied (7 items), dismissing (5 items), and fearful (5 items). These 24 items are answered on a 5-point Likert scale (– 1 = *strongly disagree*, – 0.5 = *disagree*, 0 = *neutral*, 0.5 = *agree*, 1 = *strongly agree*). The choice for the ASQ was guided by its strong psychometric properties and validation with several samples, including Dutch[72]. The ASQ instrument was developed based on the Relationships Scale Questionnaire[73]. The ASQ has shown acceptable test-retest reliability and good construct validity[72]. Notably, this is not a clinical assessment of early parent-child experiences[56,74]. Only the preoccupied and dismissing subscales were used in the analyses. In our sample, the dismissing and the preoccupied subscales yielded Cronbach's alpha coefficients of 0.74 and 0.85, respectively, suggesting moderate to high internal consistency.

Statistical analyses

To test the effect of attachment orientation on pupil response to happy and sad facial expressions, we applied a linear mixed-effects model (function 'lmer'; package 'lme4' in R; Bates et al., 2014), fitted with residual maximum likelihood (REML). The data and code to reproduce the analyses are available on GitHub. Emotion (happy, sad) and the interaction between Emotion and Dismissing and Preoccupied attachment were treated as fixed effects. Intercept, participant, mean luminance and trial number were treated as random effects. Sensitivity analyses with age and sex as additional fixed effects in the model showed comparable results. Additional correlation analyses were performed to check whether baseline activation is related to variation in attachment orientation.

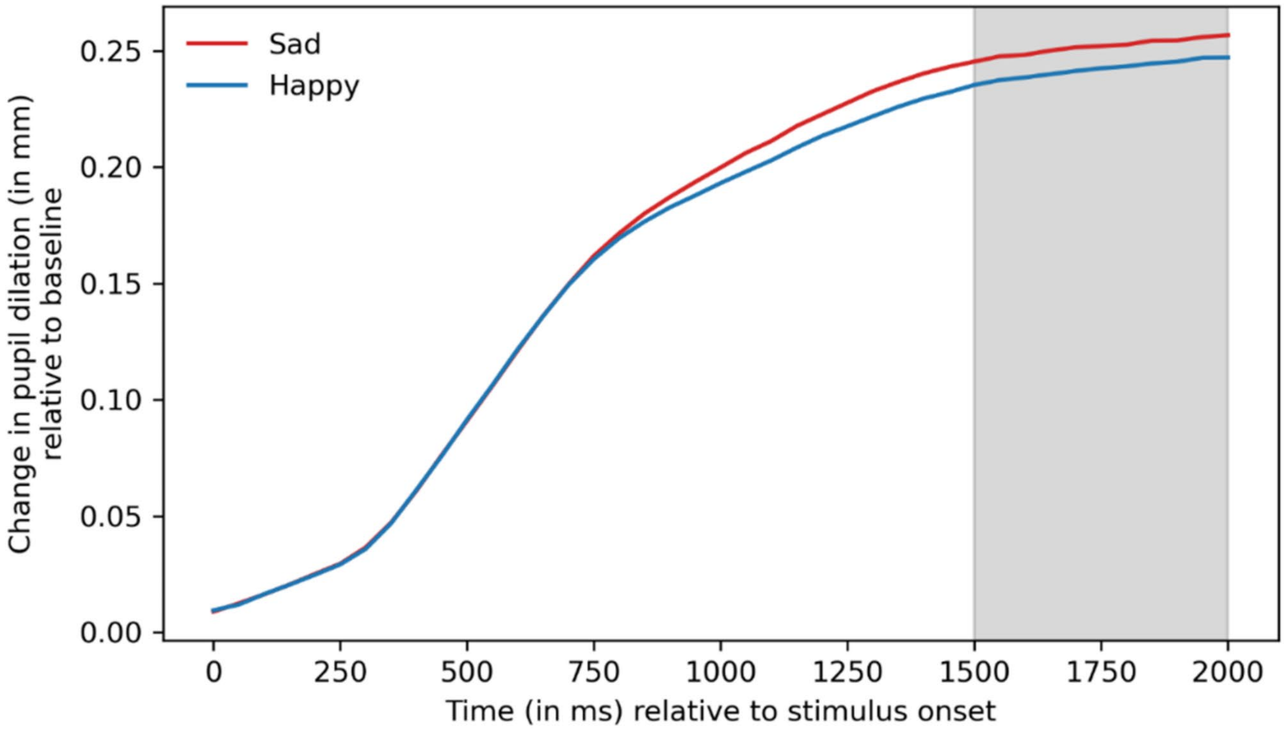

Fig. 3. Pupil responses across time. Time series of change in pupil dilation (in mm) from baseline as a function of time of stimuli presentation (sad facial expressions in red; happy facial expressions in blue). The grey shading highlights the 500ms window used in the analyses.

Data availability

Data Availability: The datasets generated and/or analyzed during the current study are available on GitHub [https://github.com/SpiessSolution/Attachment_PupilDilation].

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Author contributions
SVV designed the study, collected and curated the data, and performed the data cleaning, pre-processing, analyses, and interpretation of the results. She wrote the manuscript. TEAW supported the interpretation of the results and provided feedback on the manuscript. SH supported the study design and interpretation of the results and provided feedback on the manuscript. SH obtained funding for the study. All authors contributed and approved the final manuscript as submitted.

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