Increased pupil dilation to happy faces in children with hyperactive/impulsive symptoms of ADHD

Attention-deficit/hyperactivity disorder (ADHD) is associated with disrupted emotional processes, including impaired regulation of approach behavior and positive affect, irritability, and anger. Enhanced reactivity to emotional cues may be an underlying process. Pupil dilation is an indirect index of arousal, modulated by the autonomic nervous system and activity in the locus coeruleus-noradrenergic system. In the current study, pupil dilation was recorded while 8 to 12- year old children (*N =* 71, 26 with a diagnosis of ADHD; 45 typically developing), viewed images of emotional faces. Parent-rated hyperactive/impulsive symptoms were uniquely linked to higher pupil dilation to happy, but not fearful, angry, or neutral faces. This relation was not explained by comorbid externalizing symptoms. Together, these results suggest that hyperactive/impulsive symptoms is associated with hyperresponsiveness to approach-related emotional cues across a wide range of symptom severity.

**Keywords: Attention-deficit/hyperactivity disorder (ADHD); Positive emotionality; Face perception; Pupil dilation; Arousal**

Attention-deficit/hyperactivity disorder (ADHD) is a diagnosis based on the presence of two symptom dimensions, *inattention* and *hyperactivity/impulsivity* (American Psychiatric Association, 2013). Although these symptom dimensions are highly correlated, they are considered to be dissociable, and consequently, ADHD presentations characterized by either both, or primarily by one of them are acknowledged. It is increasingly recognized that ADHD symptoms are continuous, with the full syndrome representing the extreme end of traits found in the general population (Coghill & Sonuga-Barke, 2012; Greven, Asherson, Rijsdijk, & Plomin, 2011). In support of the dimensional view, studies have found the genetic factors related to ADHD as a diagnosis and to the broader phenotype to be highly similar (Demontis et al., 2019). ADHD symptoms are associated with negative social and educational outcome and psychiatric comorbidity across the symptom spectrum (Holmberg & Bölte, 2014; Vogel et al., 2018) Studies of symptom dimensions rather than discrete diagnostic entities have therefore been advocated (Cuthbert, 2014). Dimensional analyses allow researchers to examine how symptoms of ADHD are associated with cognitive and physiological markers across the whole phenotypic continuum.

Despite an extensive literature documenting cognitive impairment in ADHD, it is clear that ADHD symptomatology cannot be explained with reference to cognitive deficits alone (Brocki, Forslund, Frick, & Bohlin, 2017; Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Martel, 2009; Sjöwall, Roth, & Lindqvist, 2013). Multiple pathway models of ADHD hypothesize that several factors, including emotional and motivational processes and cognitive impairments contribute to the emergence of ADHD, but their relative importance and links to diagnostic presentations are debated (Castellanos et al., 2006; Martel, 2009; Sergeant, 2000). ADHD is highly overlapping with externalizing disorders. Around 20% of diagnosed children fulfill the criteria for a comorbid diagnosis of oppositional defiant disorder (ODD) or conduct disorder (CD; Biederman, 2005; Jensen & Steinhausen, 2015). A subgroup of children with ADHD also show a pattern of blunt affect and reduced concern for others, behaviors which are termed callous-unemotional (CU) traits (P. J. Frick & White, 2008).

Although emotional disturbances are not part of the diagnostic criteria, many children with ADHD have difficulties within this area, severely affecting their everyday functioning. Both maladaptive expression of emotion and difficulties with emotion regulation are commonly described. For example, children with ADHD often react to disappointment with frustration and high levels of negative affect (Cole, Zahn-Waxler, & Smith, 1994), and are often perceived by peers and teachers as overly emotionally intense and intrusive (Diamantopoulou, Henricsson, & Rydell, 2005; Gardner & Gerdes, 2015). These emotional disturbances have most consistently been linked to hyperactive/impulsive symptoms (Martel, Nigg, & Von Eye, 2009; Sjöwall, Roth, & Lindqvist, 2013; Forslund, Brocki, Bohlin, Granqvist, & Eninger, 2016; M. A. Frick, Bohlin, Hedqvist, & Brocki, 2018).

The causes and nature of emotional disturbances in ADHD are debated. A recent review identified three potential underlying mechanisms (Shaw, Stringaris, Nigg, & Leibenluft, 2014). At the most basic level, ADHD symptoms could be associated with atypical bottom-up driven reactivity to emotional stimuli such as faces with emotional expressions. This is a process underpinned by subcortical brain circuits with altered structure and function in ADHD, including the amygdala and the orbitofrontal cortex (Hoogman et al., 2017). Secondly, disrupted reward sensitivity could contribute to emotionality by enhancing attention to immediate rewards over long-term goals. Finally, emotional impairment may be driven by impaired top-down control, linked to dorsolateral frontal brain regions. All these processes could potentially manifest in increased arousal to emotionally salient stimuli.

Task-evoked pupil-dilation responses (i.e. increases in pupil size) is a physiological index of arousal, closely linked to activity in the locus coeruleus-noradrenergic (LC-NE) system. Pupil dilation is elicited by the LC-NE system through excitation of sympathetic and inhibition of parasympathetic activity (Joshi, Li, Kalwani, & Gold, 2016; Reimer et al., 2016; Samuels & Szabadi, 2008). The LC-NE system projects to wide-spread cortical areas and enhances attention to motivationally salient stimuli (Aston-Jones & Cohen, 2005). Consequently, pupil dilation responses are elicited by salient, novel, or emotionally arousing stimuli such as emotional faces (Kleberg, Hanqvist, Serlachius, & Högström, 2019; Laeng, Sirois, & Gredebäck, 2012). Threat-related stimuli such as faces with negative emotional expressions, or words with negative valence typically elicit larger pupil dilation than stimuli with neutral or positive valence (Bradley, Miccoli, Escrig, & Lang, 2008; Hepsomali, Hadwin, Liversedge, & Garner, 2017; Kleberg et al., 2019; Price et al., 2013; Silk et al., 2007). Increased pupil dilation to positive stimuli has also been found in response to positive compared to neutral stimuli (e.g. Bradley et al., 2008; Oliva & Anikin, 2018; but see Wang et al, 2018).

Previous studies have shown that individuals with ADHD have reduced pupil dilation during cognitive task performance, suggesting difficulties with arousal regulation and effort regulation (Metin, Sonuga-Barke, Wiersema, Roeyers, & Vermeir, 2017; Wainstein et al., 2017). To our knowledge, no previous study has examined pupil dilation to emotional faces in relation to ADHD symptomatology.

It is not clear whether the disturbances of positive or negative emotion, or both, are most characteristic of ADHD. Most previous studies of emotional processes related to the ADHD phenotype have examined negative emotionality, but a growing literature suggests that disrupted expression and regulation of positive affect is also involved (e.g. Brocki et al., 2017, Beauchaine & Zisner, 2017). At first sight, it might be counterintuitive that increased positive affect would be a developmental concern. However, intense positive affect could lead to diminished social reciprocity and difficulties focusing on long-term goals (Beauchaine & Zisner, 2017; Bunford, Evans, & Langberg, 2018). Dysregulation of positive affect in ADHD may be part of general difficulties with inhibiting strong approach motivation (Brocki et al., 2017). A number of studies have reported concurrent and longitudinal links between ADHD symptoms and high levels of positive emotionality. For example, increased positive emotionality reported by parents has been found to predict ADHD symptoms longitudinally, even after controlling for cognitive functioning and negative emotionality (Forslund et al., 2016; M. A. Frick et al., 2017; Sjöwall, Bohlin, Rydell, & Thorell, 2017).

Several studies have found evidence for enhanced responses to rewarding social stimuli such as smiling faces, children and adults with ADHD (Ichikawa et al., 2014; Passarotti, Sweeney, & Pavuluri, 2010; Shaw et al., 2014). For example, hyper-responsiveness to happy faces in individuals with ADHD has been found in temporal cortical areas involved in face processing (Ichikawa et al., 2014). Other studies have found evidence for hyperreactivity in brain areas involved in reward processing such as the striatum and medial prefrontal cortex as well asin dorsolateral prefrontal areas linked to top-down regulation (Passarotti et al., 2010; Posner et al., 2011). This suggests that ADHD is linked to both atypical top-down regulation of positive emotionality and enhanced bottom-up reactivity to positive emotional stimuli.

ADHD symptoms are also associated with disrupted negative emotionality (Bunford, Evans, & Wymbs, 2015; Graziano & Garcia, 2016; Sobanski et al., 2010). Consistent with these findings, atypical responses to cues of negative affect have been reported during the earliest time stages of processing (Ichikawa et al., 2014; Romani et al., 2018). Recently, Flegenheimer and colleagues (2018) found atypical event related potentials (ERP) for fearful, but not happy or angry faces in young children with ADHD. In contrast other studies have reported atypical responses to both positive and negative emotions (Alperin, Gustafsson, Smith, & Karalunas, 2017; Tye et al., 2014).

Comorbid externalizing symptoms could potentially explain the observed link between ADHD and atypical reactivity to emotion, but this question remains largely unexplored. Like ADHD, comorbid externalizing disorders are likely to be linked to emotional problems. Some recent studies have suggested that negative emotionality and irritability is a shared feature between hyperactive/impulsive symptoms, and externalizing disorders such as ODD and CD, and not disorder specific (Sobanski et al., 2010; Steinberg & Drabick, 2015). In contrast, disrupted positive emotion processing may be uniquely associated with ADHD, and particularly with the hyperactive/impulsive symptom dimension (Beauchaine & Zisner, 2017; Martel et al., 2009).

CU traits may be linked to a different type of emotional reactivity than the larger externalizing symptom dimension (i.e. ODD and CD). CU traits have been linked to attenuated emotional arousal to cues of negative emotion in others (Dadds et al., 2016). This attenuated emotional response could lead to impaired socialization learning from signs of distress or anger in peers or parents in this group (Blair, White, Meffert, & Hwang, 2013; P. J. Frick & White, 2008). In contrast, ODD, in which aggression is primarily reactive, may instead be linked to a pattern of increased arousal to a wide range of emotional stimuli.

To sum up, although ADHD symptoms have been associated with disrupted emotional processes, questions remain about the relative importance of positive and negative emotions, the brain mechanisms involved, as well as the role of comorbid externalizing symptoms. The studies examining emotional processes in ADHD have mainly relied on group comparisons, rather than dimensional analyses. We sought to examine the relations between ADHD symptoms and pupil dilation to facial emotional expressions of both positive emotion (happiness) and negative emotion (anger and fear), while controlling for symptoms of externalizing disorders. Studies of pupil dilation have previously been conducted in various neurodevelopmental disorders as well as in typical development (Kleberg, del Bianco, & Falck-Ytter, 2018; Prehn-Kristensen et al., 2017; Sepeta et al., 2012; Wainstein et al., 2017), but to our knowledge, no previous study has examined pupil dilation to emotional stimuli in relation to symptoms of ADHD. To further characterize the correlates of the pupil dilation response, we examined its relation to parental ratings of emotionality and emotion regulation skills for the specific emotions studied.

In light of the previous literature, we hypothesized that ADHD and externalizing symptoms (ODD and CD) would be linked to higher pupil dilation to both positive (happy) and negative (angry and fearful) emotional expressions, and that CU traits would be linked to lower pupil dilation to negative emotions specifically. Successful emotion regulation could potentially be linked to both increased pupil dilation (indicating mental effort) and decreased responses (indicating reduced bottom-up reactivity). This hypothesis was therefore undirected. We also examined the relation between parental ratings of emotionality and pupil dilation, but left this hypothesis undirected.

**Methods**

**Participants**

The final sample consisted of 71 children (18 female) of which 26 had received a diagnosis of ADHD.

*Children with ADHD.* Families of children with ADHD were contacted through outpatient clinics and advertising in newspapers and social media. In total, 33 children with ADHD and their families initially agreed to participate. Of these, two were excluded because of equipment failure, five because the child eventually did not want to take part in the experiment, and one because the parents did not hand in the symptom measures. Parents confirmed that the child had received a diagnosis of either ADHD combined (ADHD-C), ADHD with primarily inattentive presentation (ADHD-PI), or ADHD not otherwise specified (ADHD-NOS) from a clinical psychologist or psychiatrist in regular care, and specified the clinic and year of diagnosis. Of the included children, one had a diagnosis of ADHD-PI, one had ADHD-NOS, and 24 had the combined presentation. Parent ratings confirmed symptom levels within the range of clinical concern according to the Swanson, Nolan, and Pelham Scale (SNAP-IV; Bussing, Fernandez, Harwood, Wei Hou, et al., 2008) in all but two cases. These children were included in the analyses, but we conducted exploratory analyses after excluding them. This did not change any of the results. Comorbid diagnoses according to medical records or parental report were dyslexia (*n* = 2), speech and language disorder (*n =* 1), and developmental coordination disorder (*n =* 1).

Eighteen children with ADHD were on medication for ADHD (metylphenidate; *n* = 12; guanfacine; *n* = 2; atomeoxetine; *n* = 1; dexamphetamine; *n* = 1; drug name not reported; *n = 2*). Families were asked to withdraw medication during the day of the experiment if possible, but four children had taken medication at the day of visit (guanfacine; *n = 2*; methylphenidate; *n = 2*). One additional participant was treated for insomnia with melatonin.

To control for potential effects of medication, we coded medication status at the day of testing as a new binary variable. Participants who either failed to washout from stimulant medication (*n =* 2), or who were treated with long-acting non-stimulants (guanfacine or atomoxetine, *n* = 3), or treated with unknown substances (*n =* 2) were coded as on medication. In exploratory analyses, we ran the analyses after removing participants on medication (*see Results*).

In addition to the children with an ADHD diagnosis, a group of typically developing children was recruited. One thousand families in the local area with children in the 8-12 years age range were randomly selected from the population registry and contacted by mail. One hundred and sixteen interested parents responded to an on-line survey, and children who matched the diagnosed children on age, sex, and when possible socio-economic status (SES) were invited and took part in the study. In total, 47 children were invited and tested. Of these, two children had no valid data due to equipment failure. None of the typically developing children had a psychiatric disorder according to parental report or questionnaires, but teacher ratings on the Strength and Difficulties Questionnaire (SDQ; Goodman, 1997) and SNAP-IV were in the clinical range for three participants (ADHD-C, conduct and emotional problems: *n* = 1; ADHD-PI: *n* = 1; emotional problems: *n =* 1) defined as scores above the 90th percentile of the national norms (Malmberg, Rydell, & Smedje, 2003). Given the aim to study symptom dimensions across the whole range, these participants were included in the analyses, but all results remained unchanged when they were excluded.

Parental education was graded on a scale from 1 (representing 9 years of schooling or less) to 6 (representing a master or doctoral degree). Income was also graded on a six-point Likert scale, with 1 corresponding to an annual income less than approximately 10 500 USD in the local currency, and 6 to approximately 52 500 USD or more). SES was operationalized as the mean of both parents’ education and income levels. IQ was estimated as the mean scaled score according to published norms (mean = 10; SD = 3) of the two sub tests Block design and Information from the Wechsler Intelligence Scale for Children (WISC, 4th Edition; Wechsler, 2003). These subtests were chosen as they had the highest loadings on full scale IQ according to published Swedish norms. IQ was missing for seven children with ADHD. As can be seen in *Table 1*, no significant group differences between children with and without ADHD were found for SES, IQ, age, or gender proportion.

(TABLE 1 HERE)

**Questionnaires**

ADHD and ODD symptoms were measured with parental and teacher ratings on the SNAP-IV (Bussing, Fernandez, Harwood, Wei Hou, et al., 2008), which asks the informant to rate the degree of severity on each of the 18 ADHD symptoms and eight ODD symptoms listed in the DSM-V criteria on a four point Likert Scale. The SNAP-IV has good psychometric properties, with Cronbach’s α ranging between good to excellent (.79 - .96) for the different subscales (Bussing, Fernandez, Harwood, Cynthia, et al., 2008). Parents and teachers were also asked to indicate the presence of the DSM-5 CD symptoms on the same scale. CU traits were measured with the Inventory of Callous-Unemotional Traits (ICU; Essau, Sasagawa, & Frick, 2006).

Parents completed the Emotion Questionnaire (Rydell, Thorell, & Bohlin, 2003), which asks the informant to rate the child’s degree of emotionality and regulation efficiency for specific emotions. The questionnaire gives separate measures for emotionality (i.e. the degree of emotional reactivity) and regulation. Separate measures calculated for specific emotions (i.e. fear, happiness, and anger). Questions are scored on a scale ranging from 1 to 5, with higher values indicating greater difficulties with emotion regulation and emotionality. A validation study reported high test–retest reliability and high construct validity with Cronbach’s α between .87 and .93 (Rydell et al., 2003). Here, ratings of regulation and emotionality of the emotions studied in the experiments were used.

Teachers completed the SDQ (Goodman, 1997), a screening measure for emotional symptoms, conduct and peer problems, and symptoms of hyperactivity/impulsivity. The SDQ also gives a total difficulties score, which is a composite measure for psychopathology. SDQ scores were not used in the main analysis, but as a screening measure for undetected psychopathology (see *Participants*). All teacher ratings were missing for 16 children (7 with ADHD, 22.5% of the final sample), resulting in a sample size of 54 children (19 with ADHD) with valid teacher ratings.

**Experimental Paradigm**

Stimuli were images of emotional faces from a standardized database (Lundqvist, Flyckt, & Öhman, 1998) shown one at a time in randomized order. The task was designed to rule out mental effort associated with explicit emotion recognition as a confounder, and stimuli that were likely to be easily identified were therefore selected. This was confirmed, as proportion of correctly identified images was close to ceiling (93.2%). The identification rate was also plotted for each stimulus image separately. The analysis showed that the identification rate exceeded 80% for all images except one, which had an identification rate of 50%. Results did not change when this stimulus was removed, and it was therefore retained. Example of stimuli are shown in Figure 1.

Images were cropped to show only the inner regions of the face. In total, 32 images were shown to each participant, evenly distributed between four conditions: three emotional expressions (angry, happy, fearful) and neutral faces (n = 8). The same actors appeared once with each expression, meaning that the stimulus set contained eight unique actors (50% male, 50% female). Stimuli were presented for four seconds, and were preceded by a fixation cross on a uniform gray screen for 1.5 seconds. Directly after the offset of the stimulus, participants were asked to identify whether the depicted person felt angry, happy, fearful, or was emotionally neutral.

(FIGURE 1 HERE)

**Data Recording**

Gaze and pupil data were recorded with a corneal reflection eye tracker (Tobii TX120, Tobii inc, Danderyd, Sweden) at a sample rate of 60 HZ. Participants viewed the stimuli from an approximate distance of 60 cm on a 17” monitor. The testing took place in a quiet room at either the Psychology department at Uppsala University or an outpatient clinic. For practical reasons, it was not always possible to run the experiment in the same rooms, and illuminance varied slightly between sessions. We aimed at an ambient illuminance of approximately 460 lux, but this was not always possible to attain. Illuminance was therefore measured before each experimental session. Post hoc analyses showed no relation between illuminance level and the pupil dilation response (*p = .*35). This was expected, since task-evoked changes in pupil dilation are largely independent of baseline pupil size (Beatty & Lucero-Wagoner, 2002).

**Preregistration and analysis plan**

The analysis plan and hypotheses were preregistered in the Open Science Framework (link: <https://osf.io/vhj6q/registrations>)

**Data Processing**

Data were analyzed using custom scripts written in MATLAB (Mathworks, Inc.). A linear interpolation was used over gaps in the pupil data shorter than 200 ms. The pupil signal was then smoothed with a moving median filter with a window size corresponding to 200 ms. The pupil dilation response was defined as the median pupil size during a 750-4000 ms time window after stimulus onset, expressed as proportion of baseline pupil size. Baseline pupil size was estimated for each participant as the median pupil size during the 0-250 ms time window of all valid trials. This time window was chosen to exclude an initial decrease in the pupil dilation curve caused by changes in luminance directly after stimulus onset (see Figure 2). Gaze coordinates were filtered using dispersion-based fixation filter (Tobii fixation filter) with velocity and dispersion threshold set to 1o of the visual field. Individual samples were removed if the gaze coordinates were outside the face. Trials were rejected if less than 25% of the samples were valid (7.3% of all trials), or if the participant failed to identify the emotional expression (6.8% of all trials), since misinterpretation of the emotional expression could potentially affect the pupil response. Finally, data from individuals contributing less than three valid trials in a condition were removed from that condition (Angry: *n* = 2; Fearful; *n* = 4; Happy: *n* = 1).

(FIGURE 2 HERE)

**Statistical Analysis**

Data were analyzed with linear mixed effects models (LMMEs) including random intercept for individual (i.e. treating multiple observations from one individual as repeated measures), trial (i.e. accounting for potential effects of trial order), and the actor displaying the emotion. Random intercept for ‘actor’ served to control for minor visual idiosyncratic features of the included images. The pupil dilation response was the dependent variable in all analyses.

Fixed effects for emotion, hyperactive/impulsive, inattentive, ODD, CU, and CD symptoms were added together to examine the link between these variables and the pupil dilation response. Two-way interaction terms between symptom measures, sex, and emotion were initially included but dropped from the final models if statistically non-significant (*p* > .05).

To analyze the link between emotion regulation impairment and pupil dilation, separate LMMEs were fitted for each emotion with parental ratings of the ability to regulate the emotion in question, and emotionality of the emotion in question.

The analyses were conducted using the ‘fitlme’ function in MATLAB. LMMEs are preferable to general linear models in data sets with multiple trials per individual, since they can account for both inter- and intraindividual variance, and do not require listwise deletion of individuals with invalid data from some, but not all conditions (Baayen, Davidson, & Bates, 2008). The significance of the individual predictors was tested by comparing models with and without the predictor in question using likelihood ratio tests (LRT), that is by examining whether the model fits the data better if the predictor is included. The omnibus significance of models with multiple predictor variables was tested against a null model including only the intercepts.

All variables were z-transformed prior to analysis for ease of interpretation. Effect sizes are reported in the unit of these z-transformed values. These values represent the slope of the linear relations for continuous variables, and pairwise post hoc contrasts in categorical comparisons (*Δb*). Sex and age were included as covariates in all analyses. Collinearity diagnostics showed that the variance inflation factors (VIF) were <4 for all included predictor variables in the models, suggesting no problem with multicollinearity.

The main analysis was dimensional – that is, we examined associations between symptom dimensions and pupil dilation metrics across the spectrum of symptoms. We examined the validity of this approach by testing interaction terms between group (ADHD, typically developing), emotion, and symptoms in the initial LMME model. Significant interaction effects would mean that the relation between symptoms and pupil dilation metrics would differ as a function of group, in which case the dimensional approach would not be valid (see also *Preliminary Analysis*).

Significant interaction effects between emotion and symptom dimensions were followed up with separate LMMEs for each emotion. Bonferroni corrections for multiple comparisons were used in all follow-up tests. In the analyses related to parent rated emotionality and emotion regulation, Bonferroni corrections for multiple comparisons were applied at the level of each emotion (for two comparisons). Residual plots indicated normally distributed residuals, and the LMMEs were therefore fitted with an ‘identity’ link function.

To control for a potential effect of gaze allocation on the pupil dilation response, the eye-mouth ratio (EMR) was added as covariate in all analyses. The EMR is defined as the proportion of looking time at the eyes of the total looking time at the eyes and mouth, and is therefore an index of the relative distribution of gaze to the core regions of the face.

*Power Analysis*

We conducted a power analysis using Monte Carlo Based simulation using the SIMR package (Green & MacLeod, 2016) implemented in R (R Core Team, 2013). This analysis showed that the data set had ~75% power to detect a relation between continuous symptom measures and pupil dilation responses of an effect size corresponding to 0.4 standard deviations of the symptom variable. This effect corresponds to approximately 0.3 points om the SNAP-IV rating scale (*see Table 1*), and was considered a meaningful effect. The power analysis was repeated for a sample size of *n =* 54, equal to the number of children with valid data from teacher ratings only. With this sample size, the power to detect a meaningful effect was below 55%.

To examine the generalizability of the results, we conducted additional analyses including 1) both parent and teacher ratings of symptoms, and 2) teacher ratings alone. As a large proportion of participants did not have teacher ratings, and as these analyses were not prespecified, they are reported in Supplementary Materials.

**Results**

*Preliminary Analyses*

A dimensional analysis would be problematic in the presence of significant interaction effects between group, symptom measures, and pupil dilation, since these interaction effects would suggest that the relation between symptoms and pupil dilation differs depending on group. Interaction terms between group and symptom measures, and three-way interaction terms between group, symptom measures, and emotion were therefore included in the initial model. These results are described in Supplementary Materials. As can be seen, no significant interaction effects involving group and inattentive, hyperactive/impulsive, ODD, or CU symptoms were found. Unexpectedly, a three-way interaction was found between CD symptoms, group, and emotion (p = .01). However, no follow-up tests survived Bonferroni correction for multiple comparisons (see *Supplementary materials*). There was also no group x emotion interaction (χ2 = 2.76, p = 0.599). ADHD symptoms were not significantly related to baseline pupil size (χ2 = 0.23, *p* = 0.631, *b* = -0.03, *SE* = 0.06), or to the proportion of correctly identified faces (χ2 = 3.09, *p* = 0.079, *b* = -0.02, SE = 0.01).

**Main Analysis.**

*Effects of emotion.* A main effect of emotion was found (*χ2*= 22.32; p<.001). Happy faces elicited lower pupil dilation than angry (*χ2* = 11.64, p = 0.004, *Δb* = 0.23, *SE* = 0.07), fearful (*χ2* = 13.24, p = 0.002, *Δb* = 0.24, *SE* = 0.07), and neutral faces (*χ2* = 11.42, p = 0.004, Δ*b* = 0.22, SE = 0.06) but no difference between angry and fearful faces was found (*χ2* = 0.04, p = >.5, *b* = 0.02, SE = 0.07). There were also no differences between angry and neutral (*χ2* = 0.70, p = >.5, Δ*b* = -0.05, SE = 0.06), or fearful and neutral faces (*χ2* = 1.30, p >.50, Δ*b* = -0.08, SE = 0.06) (*see Figure 2*).

*Relations between pupil dilation and symptom measures.* As can be seen in *Table 2,* no main effects of sex, age, or any of the symptom dimensions were found. However, the interaction between hyperactive/impulsive symptoms and emotion was significant (*χ2* = 9.37, *p* = 0.025). Bonferroni corrected follow-up analyses showed that the higher levels of hyperactive/impulsive symptoms predicted larger pupil dilation to happy faces (*χ2* = 9.98, *p* = 0.008, *b* = 0.30, *SE* = 0.09), but was not linked to pupil dilation to angry (*χ2*= 3.17, p = 0.30, *b* = -0.15, *SE* = 0.09), fearful (*χ2* = 0.42, *p* = >.50, *b* = 0.06, *SE* = 0.09) or neutral faces (*χ2* = <.01, *p* = >.50, *b* = -0.01, *SE* = 0.09). These results are shown in *Table 2* and *Figure 3*. No significant interaction effects were observed between emotion and the inattentive, ODD, CD, or CU symptom dimensions.

(FIGURE 3 HERE)

*Relations between pupil dilation, parental ratings of emotionality, and emotion regulation* Relations between emotion regulation, emotionality, and pupil dilation were conducted separately for each emotion. Pupil dilation to happy faces was linked to higher parental ratings of emotionality for happiness (*χ2* = 5.26, *p* = 0.044, *b* = 0.12, *SE* = 0.05) but not emotion regulation (*χ2* = 1.73, *p* = 0.39, *b* = 0.07, *SE* = 0.05). No significant relations were found between pupil dilation to angry faces and emotionality (*χ2* = 0.65, *p* >.50, *b* = -0.03, *SE* = 0.04) or regulation (*χ2* = 0.10, *p* = >.50, *b* = -0.01, *SE* = 0.04). Pupil dilation to fearful faces was also not significantly related to parent-rated emotionality (*χ2* = 0.12, p >.50, *Z* = 0.0163, *SE* = 0.05) or regulation (*χ2* = 0.41, *p* >.50, *b* = -0.03, *SE* = 0.05).

(TABLE 2 HERE)

*Teacher Ratings*

All significant results remained when the means of teacher and parent ratings were used as dependent variables. However, these effects were not significant in analyses conducted with teacher ratings only in the subset of participants with available teacher ratings (see *Supplementary Materials*). As described above, statistical power was limited in the analysis of teacher ratings due to the fact that data was available from only a subset of the sample (*n =* 54).

*Tests for medication effects*

Pupil dilation to happy faces was still significantly related to hyperactive/impulsive symptoms when children on medication at the day of testing (*n =* 7) were removed (*χ2* = 6.97, p = 0.008, b = 0.26, SE = 0.10). In contrast, the relation between parent-rated emotionality for happiness and pupil dilation to happy faces was only borderline significant after removal of these participants (*χ2* = 3.69, p = 0.055, b = 0.10, SE = 0.051).

**Discussion**

ADHD and comorbid externalizing conditions are associated with emotional disturbances, but there is an ongoing debate about the nature of these impairments. In the current study, pupil dilation responses to emotional faces were studied in a group of school-age children oversampled for individuals with a diagnosis of ADHD. In light of recent studies showing that symptoms of ADHD form a continuous phenotype (e.g. Demontis et al, 2019; Larsson et al, 2014), dimensional analyses were conducted.

Our results suggest that hyperactive/impulsive symptoms are uniquely linked to increased pupil dilation induced by happy faces, beyond the influence of inattentive and externalizing symptoms. No relation was found between responses to faces with negative expressions (anger and fear) and symptoms of ADHD or externalizing disorders. Pupil dilation to happy faces was also positively linked to parental ratings of positive emotionality, indicating that the observed increased reactivity to happy faces is related to everyday behavior. To the best of our knowledge, this study is the first to examine pupil dilation to emotional stimuli in relation to symptoms of ADHD.

The results are in line with a number of recent studies linking ADHD, and hyperactive/impulsive symptoms in particular, to dysregulation of positive emotion (Brocki et al., 2017; Forslund et al., 2016; Musser, Backs, Measelle, & Nigg, 2011; Sjöwall, Roth, Lindqvist, & Thorell, 2013), and has important implications for our understanding of emotional disturbances linked to the ADHD phenotype. Strong positive affect and exuberance may contribute to everyday impairment by enhancing focus on short-term goals and rewards. Extreme levels of positive affect could also lead to inappropriate social behavior, eventually leading to peer rejection (Bunford et al., 2015). High levels of positive affect and exuberance may also be a longitudinal predictor of hyperactive/impulsive symptoms (Forslund et al., 2016; M. A. Frick et al., 2018). Taken together, this and previous studies suggest that more adaptive regulation and expression of positive emotionality may be a promising target for interventions directed at children with hyperactive/impulsive symptoms.

The results of the main analyses remained when the mean of parent and teacher ratings were used as predictors, but not when teacher ratings alone were used. Since the analysis of teacher ratings was only possible to conduct in a relatively small subgroup of children with valid teacher ratings (particularly among children with ADHD), these results must be interpreted with caution. It is possible that the relation between hyperactive/impulsive symptoms and arousal to faces is better reflected in parent than in teacher ratings, since increased positive affect and approach behaviors may be more visible at home than in a classroom setting. However, it is also possible that the null finding for teacher ratings only results from a lack of statistical power due to data loss.

Phasic pupil dilation is caused by activity in both branches of the autonomic nervous system. It is modulated by subcortical brain structures, and particularly by the LC-NE system (Bast, Poustka, & Freitag, 2018; Laeng et al., 2012; Reimer et al., 2016). Our results therefore suggest that these mechanisms may be involved. Interestingly, studies using other methodologies have also linked emotion dysregulation in ADHD to atypical autonomic functioning (e.g. Musser et al., 2011, 2018). Our results support the use of pupil dilation as a feasible method for measuring atypical emotional processing and autonomic reactivity linked to ADHD symptoms across the continuous phenotype. The method is non-invasive and relatively inexpensive, and may therefore be applicable in a wide range of research settings.

Contrary to our hypotheses, no relations were found between pupil dilation to emotional expressions and the externalizing symptom dimensions of ODD, CD, and CU traits. This is at odds with previous literature that has linked these symptoms to disrupted processing of negative affect in others (Bunford et al., 2015; Shaw et al., 2014). It is possible that a restricted range of externalizing symptoms explain this null finding. No included children had a formal diagnosis of ODD or CD, and the level of CU symptoms was not significantly higher among children with ADHD than in the typically developing group.

Pupil dilation to happy faces was related to higher parental ratings of emotionality for happiness, as well as to hyperactive/impulsive symptoms. An interesting question for future studies is to examine whether pupil dilation metrics in conjunction with parental ratings of specific behaviors can help to identify specific subgroups within the ADHD phenotype characterized by disrupted positive emotionality (e.g. Karalunas et al., 2019).

Higher pupil dilation was observed to faces displaying negative emotions (anger and fear) compared to positive emotions (happiness). This is consistent with previous research reporting higher pupil dilation to potentially threat-related as compared to non-threatening stimuli (e.g. Price et al, 2013; Silk et al, 2007; Kleberg et al, 2019). Somewhat surprisingly, neutral faces also resulted in higher pupil dilation than happy faces. The reason for this is not clear. One possibility is that it was more cognitively demanding to recognize the neutral faces than the emotional faces. This could have resulted in an increased pupil dilation reflecting cognitive load rather than emotional arousal (Laeng et al., 2012). A second possibility is that neutral faces, although correctly identified, could have been perceived as having negative emotional valence (e.g. Cooney, Atlas, Joormann, Eugène, & Gotlib, 2006).

A limitation is that a small number of children were on stimulant and non-stimulant medication for ADHD, which is known to affect noradrenergic neurotransmission, at the day of testing. Results were highly similar when children on medication who either failed to washout, were on non-stimulant medication, or on unknown medication (total *n =* 7) were removed. However, it should be noted that the study did not have statistical power to formally test differences between children with and without medication.

An interesting venue for future studies is to examine whether pupil dilation responses can measure treatment effects on emotional impairments. A second limitation is that the diagnoses of children with ADHD were not independently confirmed. Although it is possible that some of the included children may not have reached the diagnostic threshold at an independent assessment, this is not likely to have affected the results of the dimensional analyses. Importantly, parent and teacher symptom ratings indicated a wide range of symptoms, which supports the use of a dimensional analysis. Parents of children with ADHD were asked to report comorbid diagnoses. However, since an independent clinical assessment was not conducted, it is possible that some comorbid disorders or other causes for inattention hyperactivity than ADHD may have gone unnoticed.

It should be noted that although dimensional studies can be informative about the mechanisms underlying ADHD symptomatology, they do not directly examine ADHD as a clinical diagnosis. Since the analysis in the present study was dimensional, future studies are needed to determine to what extent the results apply to ADHD understood as a categorical construct. Studies including larger samples of children with a clinical diagnosis of ADHD would also have better statistical power to examine nonlinear relations between ADHD symptoms and pupil dilation, such as interactions between diagnosis, symptom level, and pupil dilation.

Finally, it should be noted that although a relation between parental ratings of emotionality and pupil dilation to happiness was found, the effect was relatively modest, and needs replication in future studies.

To sum up, we found that hyperactive/impulsive symptoms were uniquely related to increased pupil dilation to happy faces, after controlling for inattentive and comorbid externalizing symptoms. This finding contributes significantly to our understanding of emotional processes linked to ADHD symptoms.

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