Restricted visual scanpaths during emotion recognition in childhood social anxiety disorder

Johan Lundin Kleberg¹, Emilie Bäcklin Löwenberg¹, Jennifer Y.F. Lau², Eva Serlachius¹,
Jens Högström¹

1. Centre for Psychiatry Research, Department of Clinical Neuroscience, Karolinska Institutet, & Stockholm Health Care Services, Region Stockholm, Stockholm, Sweden
2. Institute of Psychiatry, Psychology and Neuroscience, King's College London, London, United Kingdom

Correspondence to: Johan Lundin Kleberg, Centre for Psychiatry Research, Department of Clinical Neuroscience, Karolinska Institutet, & Stockholm Health Care Services, Region Stockholm, CAP Research Centre, Gävlegatan 22, SE-113 30 Stockholm. E-mail: Johan.lundin.kleberg@ki.se

Background. Social anxiety disorder (SAD) has its typical onset in childhood and adolescence. Maladaptive processing of social information may contribute to the etiology and maintenance. During face perception, individuals extract information with a succession of visual fixations known as a scanpath. Atypically long scanpaths have been reported in adults with SAD, but no data exists from pediatric samples. SAD has also been linked to atypical arousal. Both metrics were examined in one of the largest eye-tracking studies of pediatric SAD to date

Methods. Children and adolescents with SAD ($n = 62$) and healthy controls ($n = 39$) completed an emotion recognition task. The visual scanpath and pupil dilation (an indirect index of arousal) were examined. The analysis plan was preregistered.

Results. Youth with SAD showed restricted scanpaths, a finding supported by both frequentist and Bayesian statistics. Higher pupil dilation was also observed in the SAD group, but despite a statistically significant group difference, this result was not supported by the Bayesian analysis.

Conclusions. Findings are contrary to findings from adult studies, but similar to what has been reported in neurodevelopmental conditions associated with social interaction impairments. Restricted scanpaths may disrupt holistic representation of faces known to favor adaptive social understanding.

Keywords

Social Anxiety Disorder (SAD); Child and Adolescent; Eye tracking; Scanpath; Emotion and Face Processing; Pupil Dilation

Social anxiety disorder (SAD) is a highly disabling mental health condition characterized by intense fear of social evaluation, often leading to extreme distress and avoidance of social interaction (American Psychiatric Association, 2013). SAD has a typical onset in late childhood or adolescence, and if left untreated, often takes a chronic course (Ruscio et al., 2008). Current theoretical models implicate aberrant information processing in the maintenance or development of SAD (e.g. Spence & Rapee, 2016).

So far, most studies of information processing in SAD have been conducted in adults (J. Chen, Van Den Bos, & Westenberg, 2020; N. T. M. Chen & Clarke, 2017; Hirsch & Clark, 2004). Adults with SAD tend to interpret social signals from others as indications of rejection or hostility (Hirsch & Clark, 2004), a bias that might be driven by disrupted allocation of attention, also to socially threatening stimuli (J. Chen et al., 2020; N. T. M. Chen & Clarke, 2017). Since an extensive literature has documented that the development of social attention and emotional brain mechanisms is protracted and often nonlinear, it is not clear whether these results generalize to the younger age range where SAD typically has its onset (Haller, Cohen Kadosh, Scerif, & Lau, 2015).

Current theoretical models implicate multiple factors in the development and maintenance of SAD, including genetic predispositions, cognitive biases, parenting and peer relations (Halldorsson & Creswell, 2017; Spence & Rapee, 2016). The importance of these factors may change over the course of development. The period from late childhood to early adulthood is characterized by developmental changes in the relative balance between brain functions involved in automatic emotional reactivity such as the amygdala, and those involved in top-down control of attention and emotion regulation such as the anterior cingulate (ACC) and prefrontal cortex (Wu et al., 2016). Consequently, a disrupted balance between these types of processes may be driving the onset of SAD during this developmental stage (Caouette & Guyer, 2014; Haller et al., 2015; Thorell, Bohlin, & Rydell, 2004). Late

childhood and adolescence is also a period of high plasticity and intense maturation of the social brain (Morales, Fu, & Pérez-Edgar, 2016; Wu et al., 2016). Therefore, aberrant information processing during this period is likely to have cascading developmental consequences (In-Albon, Kossowsky, & Schneider, 2010). Conversely, late childhood and adolescence may be a period when interventions tailored to address disrupted information processing mechanisms are particularly likely to carry long-term benefits (Haller et al, 2015). To understand these mechanisms is therefore an important research priority.

There is some evidence that youth with SAD misinterpret signs of both negative and positive emotions in faces (Melfsen & Florin, 2002), and show atypical functioning of brain regions involved in face processing (Frick, Howner, Fischer, Kristiansson, & Furmark, 2013; Gentili et al., 2016). However, the patterns of visual attention linked to these observed SAD-linked anomalies are poorly understood. A small number of studies have examined how socially anxious youth spontaneously distribute their attention between (socially) threatening and non-threatening stimuli (Boll, Bartholomaeus, Peter, Lupke, & Gamer, 2016; Lisk, Vaswani, Linetzky, Bar-Haim, & Lau, 2019; Seefeldt, Krämer, Tuschen-Caffier, & Heinrichs, 2014), but little is known about the way they distribute their attention to come up with judgements about emotional states.

Visual attention unfolds through a succession of fixations and saccades known as the *scanpath*. Fixated locations are highly prioritized for further cortical processing, and the scanpath is therefore a fundamental aspect of visual information processing. Cognitively demanding tasks typically lead to longer and more widely distributed scanpaths, reflecting a higher degree of mental effort (Barton, Radcliffe, Cherkasova, Edelman, & Itriligator, 2006; Dewhurst et al., 2018). Stimuli signaling potential threats may also viewed with longer scanpaths than neutral stimuli, possibly driven by increased allocation of attention (Green, Williams, & Davidson, 2003). Some types of facial information can be identified with

scanpaths consisting of as little as two fixations, including the identity of familiar individuals or emotional expressions which can be identified by a single feature (e.g. a furrowed eyebrow; Arizpe, Noles, Tsao, & Chan, 2019; Curby, Johnson, & Tyson, 2012). More typically, novel faces are scanned with multiple fixations (Bombardieri, Mast, & Lobmaier, 2009; Schwarzer, Huber, & Dümmler, 2005). A spatially distributed scanpath is believed to facilitate encoding of the face into a holistic percept (Arizpe et al., 2019; Hills, Eaton, & Pake, 2016), and improves face recognition (Chan, Chan, Lee, & Hsiao, 2018). Holistic processing is a hallmark of face processing in healthy individuals (Farah, Wilson, Drain, & Tanaka, 1998), while individuals with impaired face processing abilities, including those with neurodevelopmental disorders, often use a piecemeal or detail focused strategy (Falck-Ytter, 2008; Loughland, Williams, & Gordon, 2002; Nakahachi et al., 2008). Restricted scanpaths could be a marker of this detail-focused processing style (Heaton & Freeth, 2016). Scanpath measures could provide important information about information processing strategies in SAD but these measures have so far not been examined in pediatric samples. In contrast, a number of studies in adults have reported abnormally long scanpaths - termed hyperscanning – during face processing tasks. Hyperscanning was initially found during free viewing of static images of faces (Horley, Williams, Gonsalvez, & Gordon, 2003, 2004), and later also for dynamic stimuli during a public speaking task (N. T. M. Chen et al., 2015). Wermes and colleagues (2018) extended these findings and found hyperscanning in adults with SAD only after an anxiety induction procedure. In contrast, the type of visual stimuli (search for threat or neutral stimulus) did not modulate the results. Finally, Boll and colleagues (Boll et al., 2016) did not observe a group difference in scanpath length between adults with SAD and healthy controls during an emotion classification task. To sum up, there is growing evidence for altered scanpath lengths in adults with SAD. Since scanpath distribution affects social information processing, this could have consequences for social and emotional understanding.

So far, a small number of eye-tracking studies have been conducted in children and adolescents with SAD (Högström et al, 2019; Schmidtendorf et al, 2018; Keil et al, 2018; Kleberg et al, 2017; Capriola-Hall et al, 2020; Kleberg et al, 2020). These studies examined the relative distribution of attention between threat-related faces and other stimuli during free viewing tasks. While studies using free-viewing tasks are informative about how individuals with SAD distribute their attention between threatening and non-threatening stimuli, they do not directly examine strategies used during evaluation of facial emotions or mental states. Results from free-viewing tasks are inconclusive, with reports of both avoidance (Keil et al, 2018; Kleberg et al, 2017), prolonged monitoring of threat (Capriola-Hall et al, 2020; Kleberg et al, 2020) and age-typical allocation of attention (Högström et al, 2019). Previous studies are limited by small sample sizes, typically ranging between 20-35 individuals (for reviews, see (J. Chen et al., 2020; N. T. M. Chen & Clarke, 2017)).

Pupil dilation

In addition to visual scanpaths, we examined pupil dilation, an indirect index of arousal, closely linked to activity in the locus coeruleus noradrenergic (LC-NE) system (Aston-Jones & Cohen, 2005). Pupil dilation increases when people process cognitively demanding, emotionally salient, or novel stimuli (Laeng, Sirois & Gredebäck, 2012). Consequently, atypical pupil dilation could be a feasible index of impaired arousal processes in SAD and other forms of psychopathology. Brain imaging studies have shown amygdala hyperreactivity to threat in SAD (Frick et al., 2013; Gentili et al., 2016). Increased LC-NE activity could lead to amygdala hyperreactivity through downregulation of inhibitory GABA neurons in the amygdala (Brehl et al, 2020). In light of previous studies, it could therefore be expected that SAD would be associated with enhanced pupil dilation to emotional faces. However, this has not been found in the two studies published so far. Keil and colleagues (2018) found evidence for a blunted pupil dilation response in 10-13 year old children with

SAD compared to controls (Keil et al., 2018). A recent study from our group examined the time course of pupil dilation in a group of adolescents with SAD as well as the amplitude of the response (Kleberg, Hanqvist, Serlachius, & Högström, 2019). Although adolescents with SAD did not differ from healthy controls in pupil dilation amplitude, an atypical time course was found, characterized by a decrease in pupil dilation over the course of stimulus presentation. We sought to extend these results in a larger sample and in the current study we examined pupil dilation amplitude which is the most commonly studied measure (Laeng, Sirois, & Gredebäck, 2012).

Pre-registration

The analysis plan was pre-registered in the Open Science Framework (link: <https://osf.io/sr3qe/>)

Hypotheses:

The following hypotheses were tested:

Hypotheses 1: Youth with SAD will show longer scanpaths than healthy controls during face processing (longer total scanpath and more dispersion between fixations).

Hypothesis 2: Youth with SAD will show a blunted pupil dilation response during later stages of face processing (e.g. after initial adaptation to light).

Methods

Participants

Participants aged 10-17 years with SAD were recruited from an ongoing clinical trial evaluating the efficacy of internet-delivered cognitive behavioral therapy (ICBT) for pediatric SAD. Initially, 107 individuals with SAD were invited and 64 of these accepted to participate in the study and completed the experiment. Three participants with SAD were excluded from all analyses because of invalid data (see *Data reduction*), resulting in a sample

size of 61. A principal diagnosis of SAD was confirmed by an experienced clinical psychologist using the Anxiety Disorders Interview Schedule (ADIS; Silverman, 1996). Exclusion criteria were initiation or dose modification of psychotropic drug within the past six weeks, current psychosis, eating disorder, severe depression, suicidal behavior or other current severe mental disorder including autism spectrum disorder, or substance or alcohol abuse. Comorbid diagnoses were specific phobia ($n = 5$), generalized anxiety disorder ($n = 8$), depression ($n = 4$), attention deficit/hyperactivity disorder ($n = 3$), separation anxiety ($n = 1$) and panic disorder ($n = 1$). Two individuals with SAD medicated with selective serotonin reuptake inhibitors (SSRIs), three with stimulants (lisdexamphetamine), and one with melatonin. All results remained when these participants were excluded.

Recruitment of the control group

We planned for a control group of $n = 40$. Participants were randomly selected from the Swedish tax registry and contacted by mail. The data collection continued until the planned sample size was reached. Initially, addresses of 326 10-17 old children living in the Stockholm area were randomly selected from the Swedish tax registry. Families were sent a letter describing the purpose of the study, and were later contacted over telephone and asked to participate. Of the initial sample, 153 families did not respond to the telephone calls, and 107 declined to participate. The remaining 66 participants were asked screening questions before inclusion. Of these, 18 were excluded because of current or previous mental health diagnoses (SAD: $n = 4$, ADHD: $n = 10$, bipolar disorder: $n = 1$, chromosome abnormalities, $n = 1$, obsessive compulsive disorder, $n = 1$, autism, $n = 1$). Seven participants were initially included, but did not complete the testing procedure because no suitable time was found. The remaining 41 individuals were included and completed the testing procedure.

Control participants were assessed by a clinical psychologist using the MINI-KID (Sheehan et al., 1998). No participant in the control group had a mental health condition according to the clinical assessment. Two individuals were excluded from analysis because of invalid data, resulting in a sample size of 39. As expected, both youth- and parent reports indicated higher levels of social anxiety in the SAD group than in healthy controls (see *Table 1*). All participants in the control group scored within one standard deviation of the mean scores on LSAS-C previously reported in normative samples of youths (Olivares, Sánchez-García & López-Pina, 2009; Schmits, Heeren & Quertemont, 2014), and could therefore be considered healthy and non-anxious. Groups were matched on age and gender (*Table 1*). The sample is partly overlapping with the group studied by Kleberg et al (2020), where data from another experiment are reported.

Ethical Considerations

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. The study was approved by the Stockholm regional research ethics committee (decision number 2017/1142-31/4).

Experimental Task

Images from a standardized database of actors displaying emotional expressions were used as stimuli (Lundqvist, Flyckt, & Öhman, 1998). In total, 24 images were shown to each participant, evenly distributed between three emotional expressions (angry, happy,

fearful)¹. The same actors appeared once with each expression, meaning that the stimulus set contained eight unique actors (50% male, 50% female). Stimulus images were cropped to show only the inner regions of the face. Each trial began with a fixation cross on a uniform gray screen for 2 seconds, followed by an emotional face presented for 4 seconds. Immediately after stimulus offset, participants were asked to identify whether the depicted person felt angry, happy or fearful. Example of stimulus images are shown in *Figure 1*.

Figure 1. Example of stimulus images with actors displaying an angry (A), fearful (B), and happy (C) expression.

¹ The following images from the KDEF database were used as stimuli: ANSF07, ANSF09, ANSF33, ANSM07, ANSM08, ANSM09, ANSM32, HASF07, HASF09, HASF33, HASM07, HASM08, HASM08, HASM32, FESF07, FESF09, FESF33, FESM07, FESM08, FESM09, FESM32.

Recording and processing of eye tracking data

Data were recorded using a Tobii X-120 corneal reflection eye tracker (Tobii Inc, Danderyd, Sweden), which samples gaze at 120 Hz and pupil size at 40 Hz. Raw eye tracking data were processed using custom scripts written in MATLAB version 2019a (Mathworks, Inc). Fixations were identified using an I-VT filter (Salvucci & Goldberg, 2000) with parameters set according to recommendations by the manufacturer. Following linear interpolation of gaps in the data shorter than 100 ms, a moving average filter with a window size of 25 ms was applied to the x- and y-coordinates. Saccades were identified as periods with between-samples velocity exceeding 30 °/s, and fixations were defined as periods between saccades. Subsequent fixations within 1° were merged. Fixations shorter than 50 ms were discarded.

Two scanpath metrics were examined: 1) Scanpath length (the summed Euclidean distance between subsequent fixations); and 2) Scanpath dispersion (the root-mean-square (RMS) value of all fixations). Scanpath length reflects the total distance that gaze travels during the entire stimulus presentations, whereas scanpath dispersion how spread out the fixations are. The RMS was calculated for each trial by 1) taking the average of the squared deviations from the mean of the x- and y-values of all fixations and 2) taking the square root of these values, and 3) averaging values for the x- and y-coordinates. Higher RMS values therefore reflect a higher degree of spatial dispersion of fixations that is relatively unaffected by the total number of fixations. For example, either a high or a low number of total fixations that are spatially close would result in a small RMS value (this measure should not be confused with the RMS of individual samples within a fixation, which is sometimes used as an index of data quality). See *Supplementary materials, Figures S1-S2*, for illustrations.

Scanpath length and dispersion are expressed in degrees of visual field. To control for the fact that less valid fixation time would result in a smaller number of fixations, the scanpath measures were divided by the total valid fixation time in seconds. Trials with less than 1500 ms valid fixation time were discarded. Accumulated fixation time at the eyes and mouth are reported in Supplementary materials, but were not part of the preregistered analyses. Pupil data were filtered according to procedures described in an earlier publication (Kleberg et al., 2019). Gaps in the data shorter than 150 ms were replaced through linear interpolation and subsequently filtered by a moving median filter corresponding to 80 ms. A pupil dilation response was calculated for each trial and defined as the mean proportional change in pupil size during stimulus presentation relative to baseline pupil size. As in previous studies (Kleberg, Frick, & Brocki, 2020; Kleberg et al., 2019), the initial increase in pupil size after stimulus onset that can largely be attributed to changes in screen luminance was discarded. Based on visual inspection of the data, pupil dilation response was defined as the mean pupil size during the 1500-4000 ms interval (see *Supplementary materials, Figure S3*).

Baseline pupil size was measured during a 750 ms interval directly preceding the stimulus. An estimate of baseline pupil size was calculated for each participant by taking the mean pupil size during this interval from all valid trials. Values outside the ± 3 SD range from the mean of each participant were considered outliers and were discarded.

Statistical Analyses

Data were analyzed using generalized linear mixed effects models (GLMM) with random intercept for participant (i.e. treating multiple observations from the same individual as repeated measures). Statistical tests for an effect were performed by comparing a model including the effect to the most complex model without the effect in question (the *null model*). For example: a main effect of group can be tested by comparing the full model $Y \sim$

GROUP + (1|ID) to a null model including only the intercept: $Y \sim 1 + (1|ID)$, where Y is the response variable. Both frequentist statistics (i.e. *p-values*) and Bayesian analyses were conducted. Bayesian statistics have been proposed as an alternative to null hypothesis significance testing (NHST). In a Bayesian analysis, the relative evidence for a hypothesis and the null hypothesis given the observed data can be quantified in terms of a *Bayes factor*. As a consequence, researchers may potentially not only conclude that the null hypothesis could not be rejected, but also that it may be supported. Bayesian statistics may also be more robust to false positive results than NHST (Wagenmakers, 2007).

In a frequentist framework, the full- and null models were compared using χ^2 -tests, yielding a *p-value* for the significance of the effect (Baayen, Davidson, & Bates, 2008). The full- and null-models can also be compared using a Bayes factor (BF), expressing the relative likelihood of the two models. Following Wagenmakers (Wagenmakers, 2007), a BF is calculated from the Bayesian information criterion (BIC) values of the two models using the following equation:

$$BF_{10} = \exp^{(BIC_{H0} - BIC_{H1})/2}.$$

Where BF_{10} is the Bayes factor favoring H_1 over H_0 , with higher numbers indicating more evidence supporting H_1 . By reversing the terms, a BF_{01} can be calculated, with higher numbers indicating more support for H^0 . By convention, a $BF > 3$ indicates positive evidence for the hypothesis, a $BF > 20$ indicates strong support, and a $BF > 150$ very strong support (Wagenmakers, 2007).

For each individual, a mean of all valid trials within each condition was computed. All data from an individual and condition were rejected if less than four trials were valid. Six participants (3 with SAD) were excluded from all analyses because they were lacking data from all conditions. Cohens' *d* is reported as a standardized effect size of group

differences. Age and sex were added as covariates in all analyses. A power analysis indicated that the study had 80% power to detect small to medium effect sizes of $d = 0.2$ or higher.

Results

Preliminary Analyses. No group differences were found in the number of completed trials (see *Table 1*). As can be seen in *Table 1*, although correct identification of emotion was close to ceiling in all conditions, the SAD group was more accurate than the HC group in identifying expressions of anger, whereas no group differences were found for happy or fearful faces.

A main effect of emotion was found on scanpath length, so that scanpaths were shorter during processing of happy compared to fearful and angry expressions. No effects of emotion were found on scanpath dispersion. Expressions of anger and fear elicited higher pupil dilation than expressions of happiness. These results are shown in *Table 2*. No group differences were found in overall looking time at the eyes or the mouth (all $p > .25$, see *Supplementary materials, Table S1*).

[*Table 2 here*]

Main analysis (preregistered hypotheses)

Scanpath length. Results are shown in *Table 3* and *Figure 2* and summarized here. Scanpaths were shorter in the SAD group than in healthy controls ($\chi^2 = 9.38$, $p = .002$, $BF_{10} = 10.94$, $d = 0.54$). This effect was not qualified by any interaction effect between group and emotion ($\chi^2 = 3.60$, $p = .167$, $BF_{10} = 0.06$).

[*Table 3 here*]

Figure 2. Scanpath length in degrees of the visual field (A), scanpath dispersion (B), and pupil dilation (C) in the SAD and HC groups. Error bars show estimated marginal means and 95% confidence intervals ** $p < .01$; $p < .05$

Scanpath dispersion. Scanpaths were also less dispersed in the SAD group compared to healthy controls ($\chi^2 = 7.68$, $p = .006$, $BF_{10} = 4.68$, $d = 0.51$; see *Table 3* and *Figure 2*). Again, no interaction between group and emotion was found ($\chi^2 = 0.43$, $p = .806$; $BF_{10} = 0.01$). To sum up, restricted scanpaths were observed in the SAD group, a conclusion supported by both Bayesian and frequentist statistics.

Pupil dilation. The SAD group had higher pupil dilation than controls. The difference was statistically significant ($\chi^2 = 3.93$, $p = .044$, $d = 0.26$), but the Bayes factor indicated that the data were slightly more likely under the null hypothesis ($BF_{10} = 0.70$, equivalent to $BF_{01} = 1.43$), and that the data were therefore inconclusive (see *Figure 2* and *Table 3*). No interaction between group and emotion was found ($\chi^2 = 0.05$, $p = .792$, $BF_{10} = 0.01$).

Discussion

Social anxiety disorder in children and adolescents is associated with cognitive biases that may maintain or exacerbate symptoms. One of the factors underlying these biases may be a pattern of disrupted and inflexible allocation of attention during information processing. The current study examined visual scanpaths and pupil dilation during emotion recognition in children and adolescents with social anxiety disorder. Emotional faces are a social evaluative cue, and are as such a disorder relevant stimulus in SAD. Compared to healthy controls, youth with SAD had shorter and less dispersed scanpaths, a finding supported by both frequentist and Bayesian statistics. This result was contrary to our pre-registered hypothesis, and also contrary to what has been reported in adult studies (N. T. M. Chen et al., 2015; Horley et al., 2003, 2004) where it has been proposed that socially anxious individuals scan faces with prolonged scanpaths, reflecting hypervigilant attention towards threat (N. T. M. Chen & Clarke, 2017; N. T. M. Chen et al., 2015). Our results suggest that this attention pattern is not present in pediatric populations. Instead, a pattern of restricted scanpaths was found. As noted in the introduction, under normal attentional circumstances, wider scanpaths are observed during periods of controlled attention and mental effort. The observed pattern of restricted scanpaths in the SAD group could therefore reflect difficulties with flexible allocation of attention.

Restricted scanpaths may lead to a face processing strategy based on attention to single features rather than global configurations (i.e. holistic face processing). Importantly, the observed pattern of restricted scanpaths was not modulated by the emotional expression of the facial images, suggesting that it was not specific for threatening expressions. In fact, longer scanpaths to negative emotions (anger and fear) compared to positive (happiness) were observed in both groups, replicating previous findings in healthy populations (Gomez, Von Gunten, & Danuser, 2019; Green et al., 2003). Our results therefore suggest that children and adolescent process a broad range of stimuli atypically.

Holistic as compared to detail-focused processing is a hallmark of normal face perception. However, a piecemeal strategy can sometimes facilitate detection of negative emotional expressions such as anger (Curby et al., 2012), which can be detected based on single features (Beaudry, Roy-Charland, Perron, Cormier, & Tapp, 2014). In the current study, patients with SAD were more accurate in identifying expressions of anger than controls, and did not differ in accuracy for happiness or fear. Although this finding should be interpreted with caution due to potential ceiling effects, it suggests that restricted scanning could facilitate detection of social threats in youth with SAD without affecting detection of less threat-relevant stimuli.

The relation between restricted scanpaths and social anxiety may be bidirectional. Previous studies in nonclinical samples have demonstrated that negative mood is associated with disrupted holistic face processing (Curby et al., 2012; Xie & Zhang, 2015). Similarly, social anxiety may therefore disrupt holistic face processing. It is also possible that disrupted holistic processing exacerbates or maintains social anxiety to the extent that it reduces the ability to interpret ambiguous or complex facial information.

The observed pattern of restricted scanpaths may also reflect patients with SAD needing less information than healthy individuals to identify facial expressions as emotional. Longer scanpaths are associated with task difficulty and complexity (Barton, Radcliffe, Cherkasova, Edelman, & Intriligator, 2006; Gomez et al., 2019). The fact that longer scanpaths were observed in the control group could therefore reflect task difficulty. In support of this interpretation, Melfsen and Florin (2002) reported that children with SAD had lower perceptual thresholds for identifying facial expressions as emotional. Interestingly, restricted scanpaths to stimuli with social content have previously been reported in other conditions with known social interaction impairments, including autism (Heaton & Freeth, 2016),

schizophrenia (Loughland et al., 2002) and schizotypy (Hills et al., 2016), suggesting that it may be a transdiagnostic mechanism.

Our finding of restricted scanpaths in the SAD group are opposite to what has been described in the adult studies (N. T. M. Chen et al., 2015; Horley et al., 2004), pointing to a possible developmental difference. Social attention develops rapidly during late childhood and early adolescence (Morales et al., 2016). As noted in the introduction, impaired attentional flexibility has been proposed as an important mediating factor in the development of SAD during childhood (e.g. Thorell et al., 2004). Our results are consistent with this theory. It is possible that restricted scanning of social stimuli may have negative developmental consequences during this period, by restricting opportunities for social learning. On the other hand, the transitional phase of adolescence may involve greater plasticity at the behavioral and neural level (Haller et al., 2015), thus interventions designed to alter these processing anomalies may yield greater and longer-lasting benefits.

Our second aim was to examine pupil dilation during face processing. The SAD group had higher pupil dilation responses than healthy controls while viewing faces, regardless of their emotional expression. According to the conventional frequentist statistical analysis (i.e. inferential statistics based on p -values), this effect was statistically significant. However, the Bayesian analysis indicated that the hypothesis was marginally less likely than the null, rendering the result inconclusive. Bayesian statistics may be less vulnerable to false positives than frequentist statistics (Wagenmakers, 2007), and we believe that this result is best interpreted with caution. We were therefore not able to replicate a previously reported finding of blunted pupillary reactivity during face perception in pediatric SAD (Keil et al., 2018). A potential reason is differences in trial length between the studies, as an atypical time course of the pupil dilation response has previously been reported in SAD (Kleberg et al., 2019). For example, Keil et al (2018) used considerably longer presentation times

Some limitations should be noted. Although the present study is one of the largest eye tracking studies of pediatric SAD to date, we were not able to compare individuals with SAD to groups with other mental health conditions. Future studies would also benefit from direct comparisons between child and adult populations with SAD. Strengths of the study includes the use of a clinically well-characterized sample of treatment-seeking patients with SAD and a matched control group randomly selected from the general population.

Acknowledgements

This research was supported by Riksbankens jubileumsfond (grant numbers P18-0068:), Claes Groschinskys minnesfond, Region Stockholm and the regional agreement on medical training and clinical research between Region Stockholm and the Karolinska Institutet ([PPG 20150032](#)), The Swedish Research Council for Health, Working Life and Welfare (Forte 2014-4052) and the Centre for Psychiatry Research, Stockholm, Sweden, and the Strategic Research Area Neuroscience (StratNEURO). ES was supported by Region Stockholm (clinical research appointment 20170605). JL is receiving research funding from the UK Economic and Social Research Council (ES/T00004X/1).

References

- American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5)*. American Psychiatric Pub.
- Arizpe, J. M., Noles, D. L., Tsao, J. W., & Chan, A. W. Y. (2019). Eye movement dynamics differ between encoding and recognition of faces. *Vision*, 3(1).
<https://doi.org/10.3390/vision3010009>
- Aston-Jones, G., & Cohen, J. D. (2005). An Integrative Theory of Locus Coeruleus-

- Norepinephrine Function: Adaptive Gain and Optimal Performance. *Annual Review of Neuroscience*, 28(1), 403–450. <https://doi.org/10.1146/annurev.neuro.28.061604.135709>
- Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. <https://doi.org/10.1016/j.jml.2007.12.005>
- Barton, J. J. S., Radcliffe, N., Cherkasova, M. V, Edelman, J., & Intriligator, J. M. (2006). Information processing during face recognition: The effects of familiarity, inversion, and morphing on scanning. *Perception*, 35, 1089–1105. <https://doi.org/10.1068/p5547>
- Barton, J. J. S., Radcliffe, N., Cherkasova, M. V, Edelman, J., & Itriligator, J. M. (2006). Information processing during face recognition: The effects of familiarity, inversion, and morphing on scanning fixations. *Perception*, 35, 1089–1105. <https://doi.org/10.1068/p5547>
- Beaudry, O., Roy-Charland, A., Perron, M., Cormier, I., & Tapp, R. (2014). Featural processing in recognition of emotional facial expressions. *Cognition and Emotion*, 28(3), 416–432. <https://doi.org/10.1080/02699931.2013.833500>
- Boll, S., Bartholomaeus, M., Peter, U., Lupke, U., & Gamer, M. (2016). Attentional mechanisms of social perception are biased in social phobia. *Journal of Anxiety Disorders*, 40, 83–93. <https://doi.org/10.1016/j.janxdis.2016.04.004>
- Bombari, D., Mast, F. W., & Lobmaier, J. S. (2009). Featural, configural, and holistic face-processing strategies evoke different scan patterns. *Perception*, 38, 1508–1521. <https://doi.org/10.1068/p6117>
- Brehl, A.-K., Kohn, N., Herman Schene, A., & Fernández, G. (2020). A mechanistic model for individualised treatment of anxiety disorders based on predictive neural biomarkers. *Psychological Medicine*, 50, 727–736. <https://doi.org/10.1017/S0033291720000410>

- Caouette, J. D., & Guyer, A. E. (2014). Gaining insight into adolescent vulnerability for social anxiety from developmental cognitive neuroscience. *Developmental Cognitive Neuroscience*, 8, 65–76. <https://doi.org/10.1016/j.dcn.2013.10.003>
- Chan, C. Y. H., Chan, A. B., Lee, T. M. C., & Hsiao, J. H. (2018). Eye-movement patterns in face recognition are associated with cognitive decline in older adults. *Psychonomic Bulletin and Review*, 25(6), 2200–2207. <https://doi.org/10.3758/s13423-017-1419-0>
- Chen, J., Van Den Bos, E., & Westenberg, P. M. (2020). A systematic review of visual avoidance of faces in socially anxious individuals: Influence of severity, type of social situation, and development. *Journal of Anxiety Disorders*.
<https://doi.org/10.1016/j.janxdis.2020.102193>
- Chen, N. T. M., & Clarke, P. J. F. (2017). Gaze-Based Assessments of Vigilance and Avoidance in Social Anxiety: a Review. *Current Psychiatry Reports*, 19(59).
<https://doi.org/10.1007/s11920-017-0808-4>
- Chen, N. T. M., Thomas, L. M., Joseph, P., Clarke, F., Hickie, I. B., & Guastella, A. J. (2015). Hyperscanning and avoidance in social anxiety disorder: The visual scanpath during public speaking. *Psychiatry Research*, 225, 667–672.
<https://doi.org/10.1016/j.psychres.2014.11.025>
- Curby, K. M., Johnson, K. J., & Tyson, A. (2012). Face to face with emotion: Holistic face processing is modulated by emotional state. *Cognition and Emotion*, 26(1), 93–102.
<https://doi.org/10.1080/02699931.2011.555752>
- Dewhurst, R., Foulsham, T., Jarodzka, H., Johansson, R., Holmqvist, K., & Nyström, M. (2018). How task demands influence scanpath similarity in a sequential number-search task. *Vision Research*, 149, 9–23. <https://doi.org/10.1016/j.visres.2018.05.006>

- Falck-Ytter, T. (2008). Face inversion effects in autism: A combined looking time and pupillometric study. *Autism Research, 1*(5), 297–306. <https://doi.org/10.1002/aur.45>
- Farah, M., Wilson, K., Drain, M., & Tanaka, J. (1998). What is “special” about face perception? *Psychological Review*. Retrieved from <http://psycnet.apa.org/journals/rev/105/3/482/>
- Frick, A., Howner, K., Fischer, H., Kristiansson, M., & Furmark, T. (2013). Altered fusiform connectivity during processing of fearful faces in social anxiety disorder. *Translational Psychiatry, 3*. <https://doi.org/10.1038/tp.2013.85>
- Gentili, C., Cristea, I. A., Angstadt, M., Klumpp, H., Tozzi, L., Phan, L., & Pietrini, P. (2016). Beyond emotions: A meta-analysis of neural response within face processing system in social anxiety. *Experimental Biology and Medicine, 241*, 225–237. <https://doi.org/10.1177/1535370215603514>
- Gomez, P., Von Gunten, A., & Danuser, B. (2019). Eye gaze behavior during affective picture viewing: Effects of motivational significance, gender, age, and repeated exposure. <https://doi.org/10.1016/j.biopsycho.2019.06.001>
- Green, M., Williams, L., & Davidson, D. (2003). In the face of danger: Specific viewing strategies for facial expressions of threat? *Cognition & Emotion, 17*(5), 779–786. <https://doi.org/10.1080/026999303002282>
- Halldorsson, B., & Creswell, C. (2017). Social anxiety in pre-adolescent children: What do we know about maintenance? *Behaviour Research and Therapy, 99*, 19–36. <https://doi.org/10.1016/j.brat.2017.08.013>
- Haller, S. P., Cohen Kadosh, K., Scerif, G., & Lau, J. Y. F. (2015). Social anxiety disorder in adolescence: How developmental cognitive neuroscience findings may shape

- understanding and interventions for psychopathology. *Developmental Cognitive Neuroscience*, 13, 11–20.
- Heaton, T., & Freeth, M. (2016). Reduced visual exploration when viewing photographic scenes in individuals with Autism Spectrum Disorder. *Journal of Abnormal Psychology*, 125(3), 399–411. <https://doi.org/10.1037/abn0000145>
- Hills, P. J., Eaton, E., & Pake, J. M. (2016). Correlations between psychometric schizotypy, scan path length, fixations on the eyes and face recognition. *The Quarterly Journal of Experimental Psychology*, 69(4), 611–625.
<https://doi.org/10.1080/17470218.2015.1034143>
- Hirsch, C. R., & Clark, D. M. (2004). Information-processing bias in social phobia. *Clinical Psychology Review*, 24(7), 799–825. <https://doi.org/10.1016/j.cpr.2004.07.005>
- Horley, K., Williams, L. M., Gonsalvez, C., & Gordon, E. (2003). Social phobics do not see eye to eye: A visual scanpath study of emotional expression processing. *Journal of Anxiety Disorders*, 17, 33–44.
- Horley, K., Williams, L. M., Gonsalvez, C., & Gordon, E. (2004). Face to face: visual scanpath evidence for abnormal processing of facial expressions in social phobia. *Psychiatry Research*, 127, 43–53. <https://doi.org/10.1016/j.psychres.2004.02.016>
- In-Albon, T., Kossowsky, J., & Schneider, S. (2010). Vigilance and Avoidance of Threat in the Eye Movements of Children with Separation Anxiety Disorder. *Journal of Abnormal Child Psychology*, 38(2), 225–235. <https://doi.org/10.1007/s10802-009-9359-4>
- Keil, V., Hepach, R., Vierrath, S., Caffier, D., Tuschen-Caffier, B., Klein, C., & Schmitz, J. (2018). Children with social anxiety disorder show blunted pupillary reactivity and altered eye contact processing in response to emotional faces: Insights from pupillometry

- and eye movements. *Journal of Anxiety Disorders*, 58, 61–69.
<https://doi.org/10.1016/j.janxdis.2018.07.001>
- Kleberg, J. L., Frick, M. A., & Brocki, K. C. (2020). Increased pupil dilation to happy faces in children with hyperactive/impulsive symptoms of ADHD. *Development and Psychopathology*.
- Kleberg, J. L., Hanqvist, C., Serlachius, E., & Högström, J. (2019). Pupil dilation to emotional expressions in adolescent social anxiety disorder is related to treatment outcome. *Journal of Anxiety Disorders*, 65, 26–33.
<https://doi.org/10.1016/J.JANXDIS.2019.04.006>
- Laeng, B., Sirois, S., & Gredebäck, G. (2012). Pupillometry. *Perspectives on Psychological Science*, 7(1), 18–27. <https://doi.org/10.1177/1745691611427305>
- Lisk, S., Vaswani, A., Linetzky, M., Bar-Haim, Y., & Lau, J. Y. F. (2019). Systematic Review and Meta-Analysis: Eye-Tracking of Attention to Threat in Child and Adolescent Anxiety. *Journal of the American Academy of Child & Adolescent Psychiatry*. <https://doi.org/10.1016/j.jaac.2019.06.006>
- Loughland, C. M., Williams, L. M., & Gordon, E. (2002). Visual scanpaths to positive and negative facial emotions in an outpatient schizophrenia sample. *Schizophrenia Research*, 55, 159–170. Retrieved from www.elsevier.com/locate/schres
- Lundqvist, D., Flyckt, A., & Öhman, A. (1998). The Karolinska directed emotional faces (KDEF). Clinical Neuroscience, Psychology section, Karolinska Institutet.
- Melfsen, S., & Florin, I. (2002). *DO SOCIALLY ANXIOUS CHILDREN SHOW DEFICITS IN CLASSIFYING FACIAL EXPRESSIONS OF EMOTIONS?* *Journal of Nonverbal Behavior* (Vol. 26). Human Sciences Press, Inc.

- Morales, S., Fu, X., & Pérez-Edgar, K. E. (2016, October 1). A developmental neuroscience perspective on affect-biased attention. *Developmental Cognitive Neuroscience*. Elsevier Ltd. <https://doi.org/10.1016/j.dcn.2016.08.001>
- Nakahachi, T., Yamashita, K., Iwase, M., Ishigami, W., Tanaka, C., Toyonaga, K., ... Takeda, M. (2008). Disturbed holistic processing in autism spectrum disorders verified by two cognitive tasks requiring perception of complex visual stimuli. *Psychiatry Research*, 159(3), 330–338. <https://doi.org/10.1016/j.psychres.2005.08.028>
- Rapee, R. M., & Heimberg, R. G. (1997). A Cognitive-Behavioral Model of Anxiety in Social Phobia. *Behaviour Research and Therapy*, 35(8), 741–756.
- Ruscio, A. M., Brown, T. A., Tat Chiu, W., Sareen, J., Stein, M. B., & Kessler, R. C. (2008). Social Fears and Social Phobia in the United States: Results from the National Comorbidity Survey Replication. *Psychological Medicine*, 38(1), 15–28. <https://doi.org/10.1017/s0033291707001699>
- Salvucci, D. D., & Goldberg, J. H. (2000). Identifying Fixations and Saccades in Eye-Tracking Protocols. In *Proceedings of the Eye Tracking Research and Applications Symposium*. New York: ACM Press. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.68.2459&rep=rep1&type=pdf>
- Schwarzer, G., Huber, S., & Dümmler, T. (2005). Gaze behavior in analytical and holistic face processing. *Memory & Cognition*, 33(2), 344–354.
- Seefeldt, W. L., Krämer, M., Tuschen-Caffier, B., & Heinrichs, N. (2014). Hypervigilance and avoidance in visual attention in children with social phobia. *Journal of Behavior Therapy and Experimental Psychiatry*, 45, 105–112. <https://doi.org/10.1016/j.jbtep.2013.09.004>

- Sheehan, D. V, Lecrubier, Y., Sheehan, H. K., Amorim, P., Janavs, J., Weiller, E., ... Dunbar, G. C. (1998). The Mini-International Neuropsychiatric Interview (M.I.N.I): The development and validation of a structured diagnostic psychiatric interview for DSM-IV and ICD-10. - PsycNET. *The Journal of Clinical Psychiatry*, 59, 22–23. Retrieved from <https://psycnet.apa.org/record/1998-03251-004>
- Spence, S. H., & Rapee, R. M. (2016). The etiology of social anxiety disorder: An evidence-based model. *Behaviour Research and Therapy*, 86, 50–67.
<https://doi.org/10.1016/j.brat.2016.06.007>
- Thorell, L. B., Bohlin, G., & Rydell, A.-M. (2004). Two types of inhibitory control: Predictive relations to social functioning. *International Journal of Behavioral Development*, 28(3), 193–203. <https://doi.org/10.1080/01650250344000389>
- Wagenmakers, E.-J. (2007). A practical solution to the pervasive problems of p values. *Psychonomic Bulletin & Review*, 14(5), 779–804. Retrieved from <https://link.springer.com/content/pdf/10.3758%2F03194105.pdf>
- White, L. K., McDermott, J. M., Degnan, K. A., Henderson, H. A., & Fox, N. A. (2011). Behavioral Inhibition and Anxiety: The Moderating Roles of Inhibitory Control and Attention Shifting. *Journal of Abnormal Child Psychology*, 39, 735–747.
<https://doi.org/10.1007/s10802-011-9490-x>
- Wu, M., Kujawa, A., Lu, L. H., Fitzgerald, D. A., Klumpp, H., Fitzgerald, K. D., ... Phan, K. L. (2016). Age-related changes in amygdala-frontal connectivity during emotional face processing from childhood into young adulthood. *Human Brain Mapping*, 37(5), 1684–1695. <https://doi.org/10.1002/hbm.23129>
- Xie, W., & Zhang, W. (2015). The influence of emotion on face processing. *Cognition and Emotion*, 30(2), 245–257. <https://doi.org/10.1080/02699931.2014.994477>

Table 1. Demographics, clinical characteristics and number of valid trials

	SAD (N = 61)		Healthy controls (N = 39)		
	Mean (SD)	Range	Mean (SD)	Range	P
Background					
Age	14.43 (2.19)	10 - 17.9	14.21 (2.21)	10.30-17.30	.618
Gender (% Female)	77	-	68		.355
LSAS (Child report) ¹	79.00 (27.78)	24 - 135	19.77 (12.25)	2 - 47	<.001***
LSAS (Parent report) ²	87.62 (26.06)	34 - 130	13.63 (12.99)	0 - 58	<.001***
CSR (Clinician)	4.89 (0.90)	4 - 7	-	-	-
Mean nr of valid trials					
Scanpath analysis	21.45 (2.73)	13 - 24	20.79 (3.42)	13.00-24.00	.311
Pupil dilation	22.92 (1.38)	18 - 24	22.62 (1.39)	19.00-24.00	.285
%Correctly identified					
Angry	98 (4)	88 - 100	94(9)	63 - 100	.009**
Fearful	95 (10)	63 - 100	95 (9)	63 - 100	>.90
Happy	99 (4)	83- 100	97 (7)	75 - 100	.203

1. Based on $n = 59$; 2. Based on $n = 58$; *** $p < .001$; * $p < .01$

Table 2. Main effects of emotion for the studied dependent variables

Scanpath Length	χ^2	P	b	SE	BF₁₀	BF₀₁	d
Fearful > Angry	1.33	.249	0.17	0.15	0.20	5.16	0.08
Angry > Happy	6.26	.012*	-0.34	0.14	2.30	0.44	0.15
Fearful > Happy	14.08	<.001***	0.51	0.13	114.91	0.01	0.22
Scanpath Dispersion							
Fearful > Angry	1.04	.307	-0.02	0.02	0.17	5.91	0.06
Angry > Happy	1.18	.277	-0.03	0.02	0.18	5.52	0.07
Fearful > Happy	0.03	.859	0.00	0.02	0.10	9.80	0.02
Pupil Dilation							
Fearful > Angry	4.85	.028*	-0.57	0.25	1.12	0.90	0.28
Angry > Happy	18.32	<.001***	-1.22	0.27	>500	<0.01	0.57
Fearful > Happy	5.92	.015*	0.65	0.26	1.89	0.52	0.29

*** $p < .001$; * $p < .05$

Table 3. *Group differences between youth with SAD and healthy controls in scanpath length, scanpath dispersion and pupil dilation response.*

	M (SD)		Group comparison					
Measure	SAD	HC	χ^2	p	BF10	BF01	d	Direction
Scanpath length (° of visual field)	7.59 (2.02)	8.82 (2.44)	9.38	.002**	10.94	0.09	0.54	SAD < HC
Scanpath dispersion	1.36 (0.32)	1.56 (0.42)	7.68	.006**	4.68	0.21	0.51	SAD < HC
Pupil dilation response	1.78 (2.20)	1.21 (2.00)	3.93	.047*	0.70	1.43	0.26	SAD > HC

** $p < .01$; * $p < .05$

Supplementary materials

A. Visualizations of scanpath metrics

Figure S1. Example of a long scanpath (A; scanpath length and RMS values above 75th percentile. Healthy participant) and restricted scanpath (B; scanpath length and RMS values below 25th percentile. Participant with SAD). Red circles represent fixations.

Figure S1. Example of a long scanpath (A; scanpath length and RMS values above 75th percentile. Healthy participant) and restricted scanpath (B; scanpath length and RMS values below 25th percentile). Participant with SAD. Colorbars show fixation density.

B. Definition of the pupil dilation response

Figure S3. Pupil trace as a function of time after stimulus onset in the SAD and HC group (across emotions). Colored areas cover means $\pm$ 95% confidence intervals. The pupil dilation response was defined as the average pupil size during the 1.5-4 seconds interval, normalized to baseline pupil size. Baseline pupil size was defined as the average pupil size during the 0.75 seconds interval directly preceding the stimulus. A fixation cross was shown during this time period.

C. Accumulated looking time at the eyes and mouth

Table S1. Effects of group (SAD, HC) and emotion (fear, anger, happiness) on looking time at the eyes and mouth.

Eyes	χ^2	P	b	SE	BF ₁₀	d
Effects of group						
Group (HC > SAD)	0.12	.730	0.01	0.03	0.11	0.07
Emotion x Group	0.05	.977	0.01	0.02	0.02	
Effects of Emotion						
Fear > Anger	1.53	.217	0.01	0.01	0.22	0.02
Anger > Happiness	16.83	<.001	0.05	0.01	476	0.29
Fear > Happiness	25.06	<.001	0.05	0.01	> 500	0.33
Mouth						
Effects of group						
Group (SAD > HC)	0.32	.575	0.01	0.02	0.12	0.09
Emotion x Group	2.41	.299	0.02	0.02	0.03	
Effects of Emotion						
Fear > Anger	2.30	.129	0.01	0.01	0.33	0.06
Happiness > Anger	24.79	<.001	0.05	0.01	> 500	0.40
Happiness > Fear	34.18	<.001	0.06	0.01	> 500	0.43