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Regular Article

Dynamic eye-tracking evaluation of responding joint attention abilities and face scanning patterns in children with attention deficit hyperactivity disorder

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Abstract

There has been growing evidence that autistic traits are more represented in children with attention-deficit hyperactivity disorder (ADHD). The purpose of this study was to investigate autistic traits associated with responding joint attention (RJA) abilities and face scanning patterns using eye-tracking in children with ADHD, and to compare with typically developing peers (TDs). All child participants viewed a series of videos related to male and female children under congruent and incongruent conditions during eye-tracking evaluation. The object and face regions of the models within the videos were determined as areas of interest (AOIs). Children with ADHD had significantly elevated ratings of autistic traits than TDs. Time course analysis of the proportion of fixations (PoF) on object region determined that children with ADHD tended to show more interest in the objects and had higher PoF on face interest area, including eyes and mouth compared to TD children in the videos when the male/female model shifts his/her gaze to the corner. Higher SRS scores were associated with higher PoF on the Face AOI in both groups. Given these findings, social skill interventions directly targeting the core deficits of RJA and problems in facial scanning appears to be beneficial in children with ADHD.

Keywords: attention deficit hyperactivity disorder; autistic traits; eye-tracking; face scanning; joint attention

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Introduction

Attention-deficit hyperactivity disorder (ADHD), which is one of the most commonly diagnosed disorders among children and adolescents, has recently been estimated to affect between 11% and 16% of school-age children (Ercan et al., 2019; Willcutt, 2012). ADHD is a lifelong neurodevelopmental disorder that can affect many areas of daily life and is associated with impairments in cognitive, academic, familial, and occupational functioning (Barkley, 2002). Moreover, poor social functioning is often one of the most debilitating negative consequences of this disorder (Hoza et al., 2005), and the impaired social skills that these children experience is considered an important factor which affects their functional prognosis (Ercan, 2015).

One factor that might contribute to social deficits among people with ADHD is a diminished capacity for social reciprocity as well as difficulties in understanding social cues (Nijmeijer et al., 2008), which could ultimately result in their failure to attend and respond appropriately to social situations (Ayaz et al., 2013). It has also been suggested that autism spectrum disorder (ASD) like characteristics are frequently observed in ADHD which can result from the similarity of signs and symptoms as well as the clinical appearance in cross-sectional evaluations (Hattori et al., 2006). Consistent with this view, several studies have identified that autistic traits were significantly overrepresented among children with ADHD versus TD (Ayaz et al., 2013; Kochhar et al., 2011; Kotte et al., 2013; Martin et al., 2014).

In recent years, eye-tracking studies have provided a reliable and objective tool for investigating cognitive processes involved in the social and communication abilities of children with ADHD regarding reported impairments in the domains of social competence such as joint attention (JA) (Marotta et al., 2014), facial emotion recognition, face scanning pattern (Airdrie et al., 2018), and sustained attention (Yıldırım Demirdöğen et al., 2022).

JA, as one of the most important indicators of early social-communicative development, is a goal-oriented behavior which involves the social coordination of one's own attention with that of another person to better adopt a common point of reference as well as share information. JA is operationalized as the ability to follow the direction of attention of other people (responding joint attention, RJA) as well as to seek to direct the attention of others in sharing the experience of an object or event (initiating joint attention, IJA) (Mundy et al., 2009). The development of

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RJA begins in the first months of life and increases the consistency of accurate attention coordination responses until the age of one. RJA, the most well known form of JA, has been extensively investigated in ASD research (Mundy, 2018). Abilities to respond to different RJA cue types including gaze shifting, head turning and pointing have been evaluated in studies (Elison et al., 2013; Stallworthy et al., 2022). RJA deficits have been reported in ASD (Chawarska et al., 2003; Riby et al., 2013; Stallworthy et al., 2022), and the broad autism phenotype (BAP), which is identified as a collection of sub-diagnostic autistic traits (Swanson et al., 2013). Similarly, impaired orientation to eye gaze shift cues has been found in children with ADHD (Marotta et al., 2014).

Researchers have investigated face processing with eye-tracking using static and dynamic social stimuli, and in doing so, have determined that children with ASD exhibit marked abnormalities in the processing of faces, including visual scanning and emotion recognition (Özer and Özdemir, 2015). Besides exhibiting limited attentional bias for faces (Katarzyna and Fred, 2010), atypical face scanning strategies have been well documented in children with ASD (Chawarska and Shic, 2009). Additionally, in most studies it is suggested that ASD children attend preferentially to the mouth and avoid the eyes, while one study failed to prove this (Rutherford and Towns, 2008). However, there is a scarcity of research on the determination of face scanning patterns in children with ADHD. It was indicated though in one cross-sectional study, that children with ADHD spend less time focusing on one's eyes than the controls, suggesting that lack of attention to the eye region of faces appears to be a characteristic of ADHD (Airdrie et al., 2018). Furthermore, a recent study has compared face scanning among children and adolescents with ASD, ADHD, and TD, and it was reported that the ADHD group gazed longer at the mouth region than other groups (Muszkat et al., 2015).

Considering the high prevalence of social deficits in children with ADHD, no studies to date have addressed the relationship between autistic features and JA abilities assessed by the eye-tracking method for this group. In the current study, the aim was to examine autistic traits in school-age children with ADHD, evaluate its relationship with RJA abilities determined by eye-tracking, and compare these with TD children. Additionally, the Social Responsiveness Scale (SRS) was used for the determination of autistic traits. The response to JA and face scanning were explored via eye-tracking, using videos in which a male and female child model looked and turned his/her head toward a corner, including both congruent (gaze toward the object) and incongruent (gaze to a different location) conditions. We hypothesized that the SRS scores would be different between children with ADHD and TD children (hypothesis 1). We also hypothesized the two groups would differ in proportions of fixations (PoFs) on the object region over time in the eye-tracking paradigm (hypothesis 2) as well as in the PoFs on the model's face in the videos, including the eye and mouth regions (hypothesis 3). Finally, we predicted that their PoFs on the object and face area of interests (AOI) would interact with the SRS scores (hypothesis 4).

Methods

Participants

The sample consisted of a total of 60 Turkish male children; those who were newly diagnosed with ADHD ($n = 30$) and a group of TD children ($n = 30$) without any psychiatric diagnosis. The ADHD group consisted of male children aged 6–10 years old identified at the Ankara University, Faculty of Medicine, Child and Adolescent outpatient clinic, after being diagnosed with ADHD according to the criteria of the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5). Additionally, all the participants with ADHD were drug-naïve children. Among the ADHD group, a total of 25 out of the 30 children met the criteria for ADHD/combined presentation as well as five of them met the criteria for ADHD/predominantly inattentive presentation. The control group consisted of age-matched TD children without any psychiatric disorder from the General Pediatric Clinic, who had been admitted for minor acute conditions such as a common cold, constipation, and so forth. The exclusion criteria for both groups included having received any psychotropic drugs, having any previous psychiatric, neurological (i.e., epilepsy) or chronic diseases (i.e., type 1 diabetes), and/or uncorrected visual and hearing impairments. Furthermore, no racial or ethnic minority groups were represented in this study.

The research protocol was approved by the Ethics Committee of Ankara University Faculty of Medicine (Ethics approval number: 12-808-18). The children, along with their parents, who accepted to participate in this study were invited and informed about the research procedures. Informed consent was obtained from all participants.

Procedure

All the participating children underwent two sessions: a clinical assessment and an eye-tracking experiment. The clinical assessment procedure consisted of a clinical interview as well as an intellectual level assessment of children and a parental report-based evaluation of psychiatric symptoms of the children.

Additionally, the sociodemographic characteristics of the participants were evaluated using a "sociodemographic questionnaire" administered by a child psychiatrist. The intellectual levels of the children were determined using the WISC-IV (Wechsler Intelligence Scale for Children – Fourth Edition) by a licensed clinical psychologist. At that time, the parents were also asked to complete the psychiatric scales. The clinical assessment sessions each lasted approximately 120 min. In the second part of the assessment, an eye-tracking experiment session was conducted in Ankara University Linguistics Laboratory (diLab, http://dilab.ankara.edu.tr/en/home/) with each of the participating children individually. The eye-tracking paradigm that was followed, evaluates how children allocate their visual attention when viewing video clips displaying female/male Turkish models who gaze at a series of targets which appear and disappear in the four corners of the assessment screen. Each of the eye-tracking sessions lasted approximately 30 min.

Clinical measurements

A sociodemographic questionnaire was used to identify a variety of social and demographic factors, including age, disease history of the child, number of siblings and parents' age, educational level, family structure, and family income. This form was completed by the researchers by asking parents these questions during the initial interview.

K-SADS-PL (Schedule for Affective Disorders Schizophrenia for School-Age Children - Present and Lifetime Version), a semi-structured interview that was originally developed by Kaufman et al. (2016), is widely used for diagnosing child psychiatric disorders. An updated version according to DSM-5 diagnostic criteria, called "K-SADS-PL-DSM-5," includes three components: an unstructured introductory interview at the beginning, followed by a screening interview which evaluates more than 200 symptoms, and finally, diagnostic supplements in the end (Kaufman et al., 2016). The K-SADS-PL-DSM-5 Turkish version has been found to be valid and reliable (Ünal et al., 2019). In this study, clinical psychiatric evaluations of all the children were conducted via K-SADS-PL-DSM-5.

SRS (Social Responsiveness Scale) is a 65-item parent-report questionnaire developed by Constantino et al. (2003) used to assess autistic traits among children and shown to have high reliability and validity (J N Constantino and Gruber, 2005; John N Constantino et al., 2003). Each item rates the frequency of a particular behavior on a 4-point Likert scale (0–3 points), with responses ranging from 0 = "*not true*," to 3 = "*almost always true*," with higher scores indicating a higher degree of autistic symptoms. In a large sample study of school-age children by Ünal et al. (2009), the SRS-Turkish version was found to be valid and reliable (Cronbach's alpha value = 0.86; Pearson's $r = 0.53$, $p < 0.001$) (Ünal et al., 2009). In the current study, SRS was used to assess autistic traits among children.

Conners' Parent Rating Scale-Revised Long Form (CPRS:R-L) is a widely used parent report scale identifying the extent of ADHD and is known for being extremely good at differentiating between individual's with or without ADHD. The scale consists of 80 items and each item is scored on a 4-point Likert scale. Symptoms are scored 0 = "*never,*" 1 = "*occasionally,*" 2 = "*often,*" and 3 = "*always*." The CPRS:R-L includes *DSM-IV* Symptom Subscales which are specific to ADHD: "Inattention," "Hyperactivity-Impulsivity," and "Combined" (Conners et al., 1998). The reliability and validity study for the scale in Turkish was conducted by Kaner et al., (2011). In the current study, this scale was used for screening ADHD symptoms and symptom severity.

Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV) is the latest revision of a well-respected and widely used general intelligence test developed in 2003 for assessing the intellectual ability of children aged 6 to 16 years old (Wechsler, 2003). The standardization and norm study for the WISC-IV Turkish version was carried out within the Turkish Psychological Association during 2007–2011 (Uluç et al., 2011).

Eye-tracking experiment

The eye-tracking stimuli for measuring joint attention was adapted from Swanson et al. (2013). In the current study, the children were presented a series of 16 colored videos which displayed the head and face of both male and female models and that also included four gaze shift trials in congruent and incongruent conditions (see Figure 1 for a detailed timeline). Thus, the actual experiment consisted of 16 trials per participants (total 960 events, 480 for Control and 480 for ADHD group). In the videos, the only clue for the participants is not only the male and female models' gaze shifts, but the models also turn their heads. It has been suggested that reliably responding to less redundant cues (e.g. only gaze shift or only head turn) indexes developmental advances in social communication for the relationship between the degree of gaze shifting and the complexity of the child's social communication responsiveness skills (Butterworth and Jarrett, 1991; Deák et al., 2008; Elison et al., 2013). In this study, we use the term "gaze shifting" to cover head turning. Because children's preferences may change for different gender (Shutts, 2015), both female and male models were included, and the race and ethnicity of face stimuli were similar with those of the participants.

At the center of the screen, each video displayed the face of a male or female model, while the targets appeared and disappeared in each of the four corners of the screen. Additionally, half of the videos were designed as congruent (gaze following the object on the screen), while the other half were incongruent (gaze directing elsewhere). The videos began with the male or female model looking straight into the camera for 4000 milliseconds (ms) in Time Window-1 (TW-1). Next, an object (LEGO®) appeared in one of the four corners of the screen, and then 700 ms later the male/female model shifted his/her gaze to a corner and held his/her gaze for 4250 ms in Time Window-2 (TW-2) with either a congruent (the corner where the object appeared) or incongruent (the opposite corner with no object) gaze. Afterward, the object disappeared while the model continued gazing at the corner (500 ms). Finally, the male/female model shifted their gaze to the center of the screen and the next trial began.

The participants' eye movements were measured using a binocular remote eye-tracking device (RED, SMI Senso Motoric Instruments) with a 500 Hz sampling rate. The eye-tracker unit was mounted below the screen. The eye-tracker system can operate at a distance of 0.5–1.5 m with a spatial resolution of approximately 0.1 degrees. The laboratory had soft-lighting and was isolated from external noise. The participants sat in front of a flat 22-inch LED monitor with a resolution of 1920 × 1080 pixels and a 60-Hz refresh rate. Their heads were stabilized using a chin rest to improve the accuracy of calibration as well as to keep the eye-to-monitor distance constant at 70 cm. Fixation detection was performed through the SMI BeGaze™ using ID-T (dispersion threshold algorithm) which was used required a minimum length of 80 ms and used a dispersion threshold of 100 pixels. Fixations under 80 ms are physically impossible and likely to be the result of blinks or noise. The eye-tracking system provides a gaze position accuracy of 0.4°. The recovery time to full tracking ability after an offset was 90 ms. The calibration and validation were performed before the start of the experiment. A nine-point calibration was used for the calibration. We repeated the calibration task until the deviation from the calibration target for both the x and y components was below 1° (calibration values: $x = 0.42$ (SD = 0.12), $y = 0.45$ (SD = 0.13) for Control group and $x = 0.46$ (SD = 0.15), $y = 0.42$ (SD = 0.16) for ADHD group).

Videos covered a rectangular space on the screen of 290 mm by 480 mm and viewed at a distance of 70 cm, and the videos corresponded to a 22.16° by 33.76° visual angle. In terms of average size, the Faces on screen were circular and 480 pixels, while the Objects were polygons and 204 pixels. Faces on screen were circular and 480 pixels in diameter (area: 180.956 pixels), while the Objects were hexagons, and its area is 68.592 pixels. Furthermore, the Face area subtended a horizontal and vertical visual angle of 9.80° × 10.52°; while the Objects subtended 4.15° × 4.45°. Thus, the distance between their centers subtended a visual angle of 15.19° on the horizontal axis and 8.51° on the vertical axis. The area of Mouth AOI is 10.731 pixels for female model and 16.443 pixels for male model, whereas the area of Eye AOI is 17.085 pixels for female model and 21.252 pixels for male model.

Statistical analysis

Analyses of clinical data

Statistical analyses of the clinical data were performed using SPSS 23.0. Prior to the analyses, the Shapiro–Wilk test was used to determine the normality of data distribution. Also, continuous

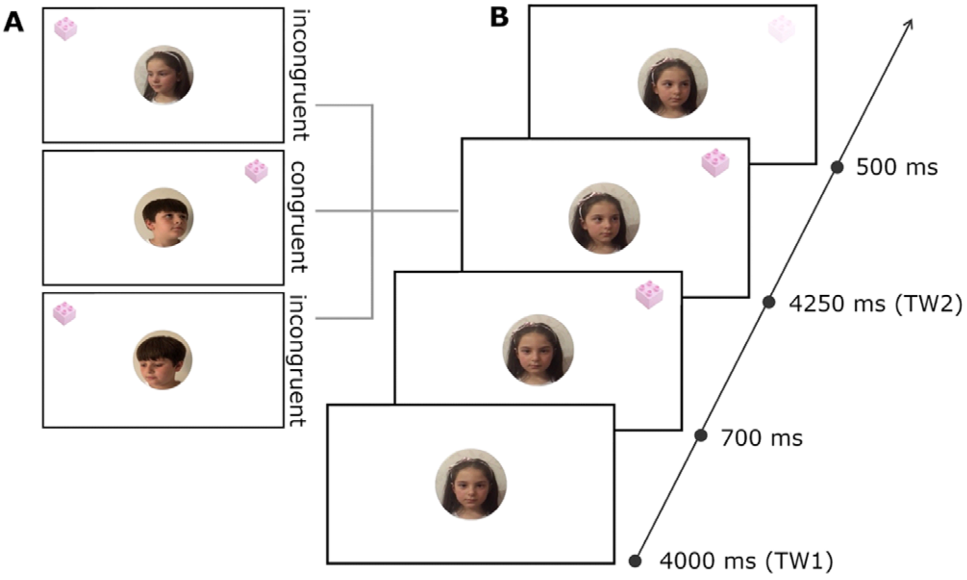

Figure 1. Congruent and incongruent conditions in videos. Panel A shows congruent and incongruent conditions for male and female children models. Congruent condition for female model is in Panel B.

clinical variables were analyzed using the independent *t* test or Mann–Whitney *U* test according to distribution characteristics within the group comparisons. Chi-square and Fisher's exact tests were used for the categorical variables, while Spearman's correlations were used to determine relationships between scale scores. Additionally, all the statistical tests were two-tailed with a threshold for significance of $\alpha = 0.05$.

The time course analysis of the eye movement data

The raw eye movement data were pre-processed in R, using the *eyetrackingR* package (Dink and Ferguson, 2015). Initially, the raw data were processed into the format required for *eyetrackingR* using R. Thereafter, for each data point, reporting was provided for the PoF to the AOIs as opposed to the non-AOIs. The PoF was a binary variable which indicated whether the participants fixated on the AOIs or not. For each frame, the AOI columns either had a value of 0 (gaze not within interest area) or 1 (gaze within interest area). Since we are interested in overall attention to each AOIs across conditions, proportion looking to each AOIs was calculated as time looking to that AOIs divided by total time looking, using the *eyetrackingR*. Only off-screen gaze was treated as trackloss and discarded. As a result, applying the *trackloss_analysis()* function in *eyetrackingR*, we calculated that 31.13% (SD = 0.09) of data points are the off-screen for the TD group and 30.35% (SD = 0.09) of those are for the ADHD group. Next, we down-sampled the data from 500 Hz to 50 Hz at the end of the pre-processing steps and transformed the PoF on the targets (i.e., AOIs), and this time used an empirical logit (Elog) transformation (Barr 2008) calculated through the *eyetrackingR* package (Dink and Ferguson, 2015).

Time course analysis based on eye movement measures may provide more valuable information than traditional approaches, which generally requires the removal of time as a variable by averaging the fixations within a specified window to avoid the issue of repeated measures through time. As a result, this analysis may yield pertinent informative data at which moment in time the conditions begin to differ as well as whether this difference is found in children with TD or ADHD. The time course of eye movements was analyzed with generalized additive mixed models (GAMMs) in R using the *mgcv* package (version 1.8-36) (Hastie, 2017), while for visualization the *itsadug* package (version 2.4) was used (Van Rij et al., 2015).

For the PoF analysis, the time course was divided into two discrete windows of interest for statistical analysis and the windows were derived from the phases of the video. For example, the first time window (TW-1) was defined as the first phase of the video and where analysis began at the video outset and extended for 4000 ms to appearance of the first target. During TW-1, the only AOIs were the Eye and Mouth. The second time window (TW-2) began at 4700 ms which was the point when the model shifted her gaze to a corner and extended it to 9450 ms. All of the windows of analysis are illustrated in Figure 1.

In our GAMM model, the PoF on the AOIs was the dependent variable, while the variables Group (TD, ADHD), Condition (congruent, incongruent), and the interaction factor between them were covariates. In favor of a smooth function in GAMM, the inclusion of the two-way interactions between Time and Group reflected the possible difference in the effect of these variables over time. As a result, the two factor smooths included were Subjects and Trial for Time. Furthermore, to account for autocorrelation in the residuals, an AR1 model was included by specifying the rho parameter and starting point for each time series (Baayen et al., 2018).

Next, to construct the optimal model, a forward and backward stepwise model-fitting procedure was used. Also, we evaluated the contribution of input variables by $\chi 2$ test of fREML scores using *compareML* function. Table S1 and S2 (in the Supplementary Material) show the final and best fit model. The parametric coefficients in the GAMM results indicated a significant difference between the reference level and the other Group-Condition interactions (see Table S1 & S2 in the Supplementary Material). To reveal differences between the two Groups (ADHD and TD), we set the contrasts of the ordered factor to contrast treatment (Wieling, 2018).

Additionally, to separately evaluate the difference between the ADHD and TD children for both the Congruent and Incongruent conditions, following the procedure illustrated in Wieling (2018), we set the contrasts of the ordered factor to contrast treatment for each of the conditions (Wieling, 2018). For example, the ordered

Table 1. Sociodemographic and clinical characteristics of groups

Sociodemographic Variables	ADHD ($n = 30$) Mean (SD)/ (Mdn (Min-Max)/*n* (%)	TD ($n = 30$) Mean (SD)/ Mdn (Min-Max)/*n* (%)	*p*
Child age (years)[a]	8.03 (1.22)	8.23 (1.33)	0.484
Mothers' age (years)[a]	36.30 (4.57)	38.07 (3.69)	0.105
Fathers' age (years)[a]	40.17 (5.54)	42.10 (4.28)	0.136
Mothers' education level[b], *n* (%)			
Less than high school	7 (23.3)	5 (16.7)	0.792
High school	9 (30)	9 (30)	
College degree or higher	14 (46.7)	16 (53.3)	
Fathers' education level[b], *n* (%)			
Less than high school	5 (16.7)	3 (10)	0.687
High school	7 (23.3)	9 (30)	
College degree or higher	18 (60)	18 (60)	
Family type[c], *n* (%)			
Intact family	28 (93.3)	29 (96.7)	1
Single parent family	2 (6.7)	1 (3.3)	
Family income[b], *n* (%)			
Low (≤330 $ monthly) Medium (330–1000$) High (>1000$)	6 (20) 13 (43.3) 11 (36.7)	5 (16.7) 13 (43.3) 12 (40)	0.935
Clinical Characteristics			
WISC-IV (score)[d]	98 (75–117)	93 (71–117)	0.387
SRS (total score)			
CPRS/DSM-IV (score) Inattentive Hyperactive-Impulsive Combined	62 (33–84) 14 (8–25) 15 (3–26) 29 (14–48)	21.5 (11–37) 2.5 (0–9) 3 (0–9) 5.5 (0–18)	**<.001** **<.001** **<.001** **<.001**

Note: Means are shown with standard deviations in parentheses, and medians are shown with minima-maxima in parantheses.
ADHD: attention-deficit hyperactivity disorder; TD: typically developing; SD: standard deviation; Mdn: median; Min: minimum; Max: maximum; WISC-IV: Wechsler Intelligence Scale for Children; SRS: Social Responsiveness Scale; CPRS: Conners Parent Rating Scale.

[a] Independent Samples *T*-Test.

[b] Chi-Square Test.

[c] Fisher's Exact Test.

[d] Mann–Whitney *U* Test.

factor "Congruent" was set to "TRUE" whenever the group equaled "TD" and the conditions was "Congruent" and "FALSE" otherwise, whereas the ordered factor "Incongruent" was set to "TRUE" whenever the group equaled "TD" and the condition was "Incongruent" and "FALSE" otherwise. The smooth functions modeled nonlinear regression lines for time and all the other factors interacting with all predictors.

Results

Sociodemographic characteristics of the groups

Both groups were found to be similar in terms of age, parental age and education level, and family characteristics ($p > .05$) (see Table 1).

Comparisons of WISC-IV profiles and scale scores

Children with ADHD had significantly higher SRS scores compared to TD children ($U = 895$, $Z = 6.582$, $\mathrm{df} = 58$, $p < .001$, $r = 0.84$). According to the CPRS: R-L DSM-IV Symptoms Subscales, *Inattentive* ($U = 898, Z = 6.644, \mathrm{df} = 58, p < .001, r = 0.85$), *Hyperactive-Impulsive* ($U = 874$, $Z = 6.286$, $\mathrm{df} = 58$, $p < .001$, $r = 0.81$), and *Total* ($U = 897$, $Z = 6.613$, $\mathrm{df} = 58$, $p < .001$, $r = 0.85$) scores were significantly higher in the ADHD group than in the TD group. Also, the WISC-IV total scores of participants from the two groups did not significantly differ from one another ($p = 0.387$) (See Table 1).

The time course analysis of the eye movement data

To analyze the eye movement data, four area of interests (AOIs) were created: face, eyes, mouth, and object area. A hexagonal area shape was placed around the objects (i.e., LEGO®) in one of the four corners of the screen (area = 68.592 pixels). The face AOI consisted of an oval shape that covered the entire face (area: 180.956 pixels). Additionally, two sub-interest areas were created which covered the eyes and the mouth (17.085 pixels for female eyes,

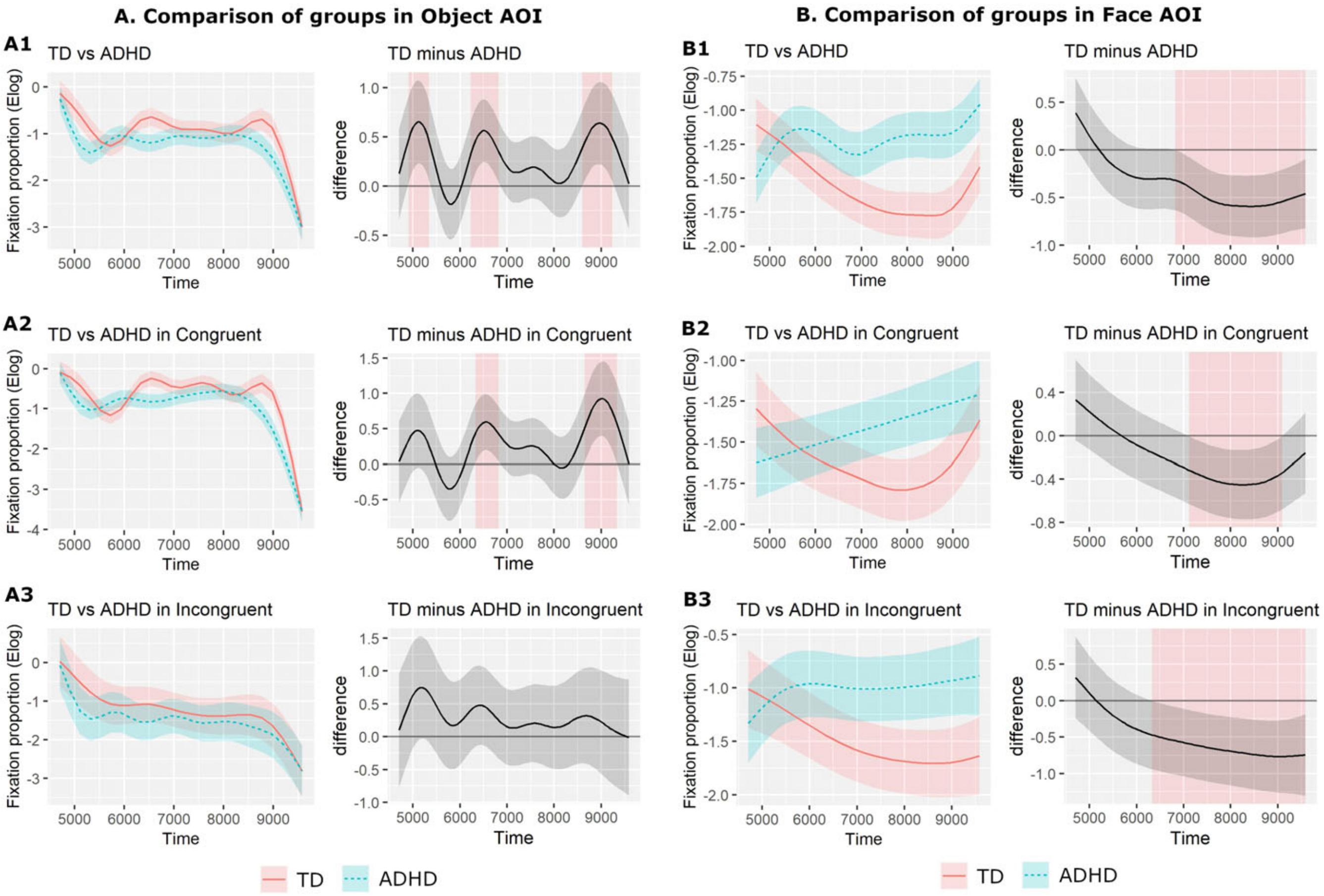

Figure 2. Comparison of groups in object and face AOIs. Smooth (left) and difference (right) plots of Group factors for the Object and Face AOIs using GAMMs. Shaded areas indicate windows of significant differences in the difference plots.

21.252 pixels for male eyes, 10.731 pixels for female mouth and 16.443 pixels for male mouth).

As we mentioned before, we used two different stimuli with male and female models. To check whether these two types of stimuli have an effect, we compared the gender of the face stimuli for all AOI (see Supplementary Material). The summary statistics which are described in Table S5 in the Supplementary Material indicate that there was no effect of any factor for TW-2, which indicated that there was no difference between the gender of the face stimuli for Object AOI ($p = 054$), Face AOI ($p = 0.13$), Eye AOI ($p = 0.99$) and Mouth AOI ($p = 0.85$). Our model included fixed effects, such as Condition and Group in this study, while simultaneously controlling for differences between trials (i.e., stimuli) and participants. As such, the by-participant and by-trial random intercepts were included as random effects. Thus, the random effect of different stimuli including male and female models was added to the model.

The object and face AOIs

In Table S1, the Supplementary Material for the final model is summarized. Based on the values in Table S1, we plotted the e-logit-transformed PoF against time as seen in Figure 2. It is shown in the figure that the e-logit-transformed PoF to the Object and Face AOIs against the time and difference plots for the Object and Face AOIs in the Groups for the TW-2. Additionally, the red shaded areas in the plots indicated that the difference was significant in these areas. As seen in Panel A of Figure 2, for both the global effect of Group (A1 of Figure 1) and Congruent condition (A2 of Figure 1), the e-logit-transformed PoF on the Object AOIs was higher for children with TD than for children with ADHD, however, there was no significant difference between groups as shown in the plot of A2 for Figure 1, which was the Incongruent condition.

Next, it is shown in Table 2, the differences using an ordered factor difference were smooth. In Table 2, ordered predictors can be identified by their variable names ending with "O": the notation of "Group.O" represented the difference between TD and ADHD groups, and the notation of "Congruent. Group.O" represented the difference between groups in the Congruent condition and "Incongruent. Group.O" for the Incongruent condition. Also, the GAMM results showed that the global effect of Group (i.e., the factor "Group.O") was significant (see Table 2 and Panel A of Figure 2). Similarly, in Table 2, the results confirmed the significance of the effect of Group in the Congruent condition (see Table 2, $p < .001$). On the other hand, there was no significant difference between the two groups in the Incongruent condition (see Table 2, $p = .10$).

In contrast to the Object AOI, which existed in only TW-2, the Face AOI existed in both TW-1 and TW-2. The summary statistics in Table 2 indicate that there was no effect of any factor for TW-1, which indicated that there was no difference between the TD and ADHD groups. As for TW-2, statistical significance was only reached in comparisons between TD and ADHD children for Congruent and Incongruent conditions ($p < .05$ & $p < .001$,

Table 2. Comparison of proportion of fixations between groups for object and face AOIs

	Time Window-1				*Time Window-2*			
Area of Interest: Object	edf	Ref.df	*F*	*p*	edf	Ref.df	*F*	*p*
s(Time):Group.O	-	-	-	-	8.12	8.28	4.38	**<.001**
s(Time):Congruent. Group.O	-	-	-	-	7.98	8.27	4.30	**<.001**
s(Time):Incongruent. Group.O	-	-	-	-	7.27	7.66	1.50	0.10
	Time Window-1				*Time Window-2*			
Area of Interest: Face	edf	Ref.df	*F*	*p*	edf	Ref.df	*F*	*p*
s(Time):Group.O	1.00	1.00	0.45	0.50	1.71	1.96	6.59	**<.01**
s(Time):Congruent. Group.O	1.00	1.01	0.08	0.78	1.98	2.37	2.94	**<.05**
s(Time):Incongruent. Group.O	1.02	1.04	0.80	0.36	3.07	3.75	4.00	**<.001**

GAMM results of the ordered factors with contrast treatment for the Object and Face AOIs, showing the parametric coefficients and approximate significance of smooth terms in the model: estimated degrees of freedom (edf), reference degrees of freedom (Ref.df), *F*- and *p*-values for smooth terms. Ordered factors with contrast treatment: Group.O = TD-ADHD contrast; Congruent. Group.O = TD-ADHD contrast of the Congruent condition; Incongruent. Group.O = TD-ADHD contrast of the Incongruent condition; s = smooth term.

Table 3. Comparison of proportion of fixations between groups for eye and mouth AOIs

	Time Window-1				*Time Window-2*			
Area of Interest:Eye	edf	Ref.df	*F*	*p*	edf	Ref.df	*F*	*p*
s(Time):Group.O	1.01	1.01	0.24	0.63	1.01	1.01	0.24	0.63
s(Time):Congruent. Group.O	1.00	1.00	0.08	0.77	1.03	1.05	6.44	**<.01**
s(Time):Incongruent. Group.O	1.00	1.01	0.41	0.52	3.13	3.82	2.68	0.05
	Time Window-1				*Time Window-2*			
Area of Interest: Mouth	edf	Ref.df	*F*	*p*	edf	Ref.df	*F*	*p*
s(Time):Group.O	6.69	7.61	1.51	0.14	1.01	1.02	0.30	0.58
s(Time):Congruent. Group.O	3.20	3.91	1.49	0.22	5.53	6.52	2.20	**<.05**
s(Time):Incongruent. Group.O	1.08	1.12	0.15	0.81	5.06	6.01	1.58	0.14

GAMM results of the ordered factors with contrast treatment for Eye and Mouth AOIs, showing the parametric coefficients and approximate significance of smooth terms in the model: estimated degrees of freedom (edf), reference degrees of freedom (Ref.df), *F*- and *p*-values for smooth terms. Ordered factors with contrast treatment: Group.O = TD-ADHD contrast; Congruent. Group.O = TD-ADHD contrast of the Congruent condition; Incongruent. Group.O = TD-ADHD contrast of the Incongruent condition; s = smooth term.

respectively, as seen in Table 2) as well as the global effect of Group ($p < .01$, as seen in Table 2). The Group effect was large in the Incongruent condition (Panel B2 of Figure 2), while it was small in the Congruent condition (Panel B3 of Figure 2). The global effect of Group was also significant (see Table 2, Panel B1 of Figure 2).

The eye and mouth AOIs

The Face AOI consisted of two different AOIs: Eye and Mouth. As a result, we performed a detailed investigation of the Face AOI. Thus, as in the case of the Face AOI, there was no effect of any factor for TW-1 in both Eye and Mouth AOIs, which is shown in the summary statistics of Table 3. Whereas for TW-2, the e-logit-transformed PoF against time concerning Face and Eye AOIs were similar in pattern where the e-logit-transformed PoF for the Face AOI (in Panel B of Figure 2) and Eye AOI (in Panel A of Figure 3) was higher for children with ADHD than for TD children. However, the statistically significant differences for Eye AOI (in Panel A of Figure 3) were very weak and late in the Congruent condition. The GAMM results of the ordered factors with contrast treatment showed a significance effect of Group in the Congruent condition (i.e., the factor "Congruent. Group.O" in Table 3, $p < .01$), but was only marginally significance in the Incongruent condition ($p = .05$), as seen in Table 3.

For the Mouth AOI, as shown in Panel B of Figure 3, the PoF on the AOI was higher for children with ADHD than the TD children. Thus, statistical significance was reached for comparisons between children with TD and ADHD in the Congruent condition ($p < .05$), however, as seen in Panel B2 of Figure 3, the difference between conditions for the ADHD group were weak and very late.

Interactions between SRS scores and eye movements

To further determine whether there could be a link between the participants' scores for the autistic traits evaluated through SRS and participants' eye movements, we added a smoothing function for the SRS-scores to the model. Therefore, the GAMM included a smoothing function for the variables SRS-scores, categorical variable Group (TD, ADHD), random effect of Trial and Subject, and the PoF on AOIs as the dependent variable. The model was similar to the previous model except that the *time* was removed and replaced by a smoothing function of the SRS-Scores.

Furthermore, the smooth plots in Figure 4 showed that children who had low SRS scores were making more fixations on the Face

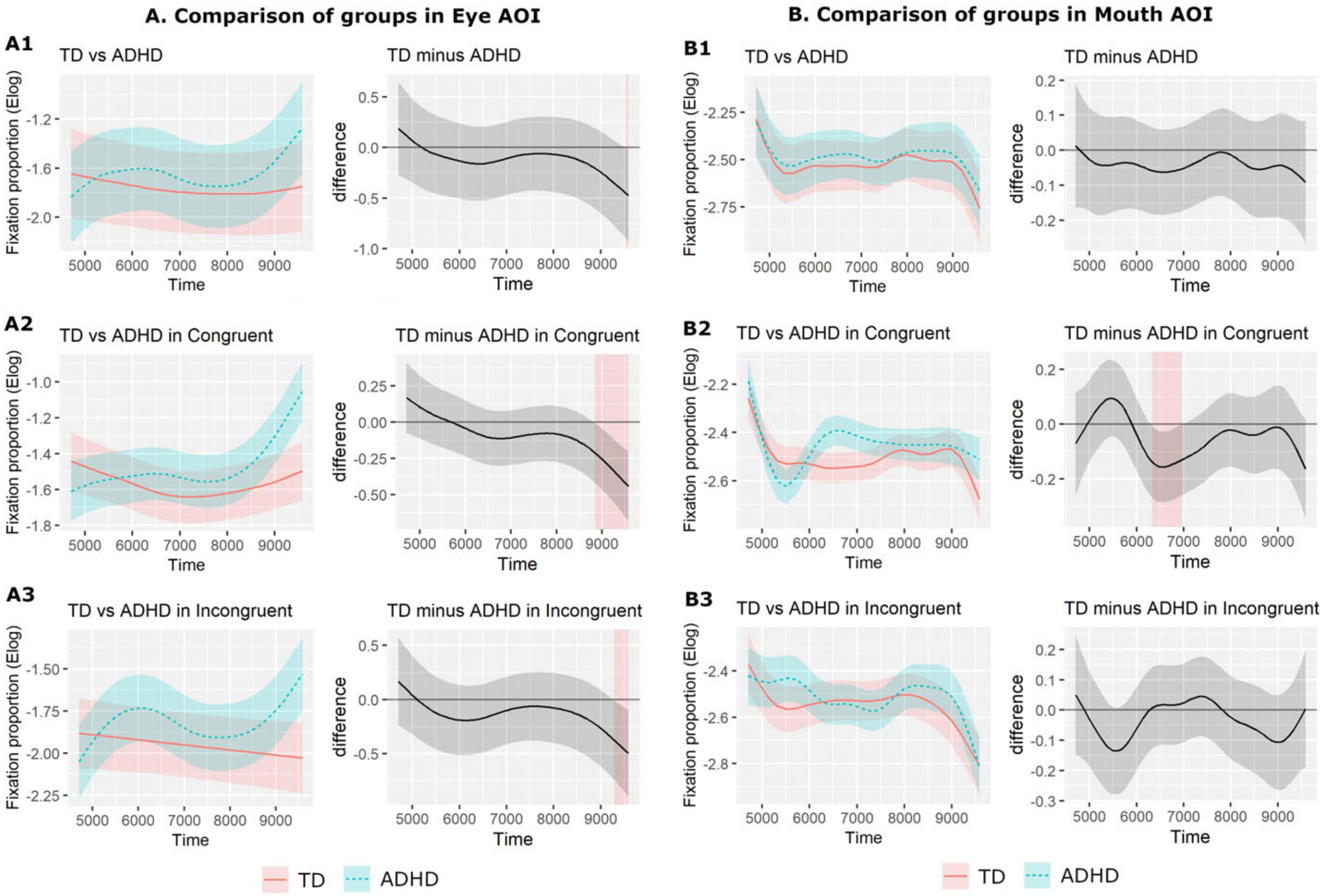

Figure 3. Comparison of groups in eye and mouth AOIs. Smooth (left) and difference (right) plots of Group factor for the Eye and Mouth AOIs using GAMMs. Shaded areas indicate windows of significant differences in the difference plots.

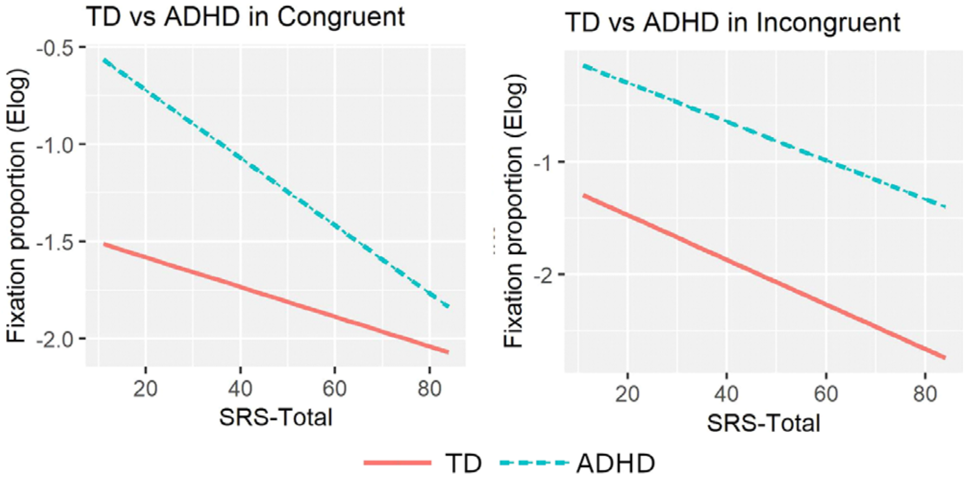

Figure 4. Interactions between fixation proportions and SRS scores in groups. Smooth plots of Group factors over the SRS-Total scores for the Face AOI in both conditions.

AOI. While the ADHD and TD group in the Incongruent condition displayed symmetrical patterns as well as a clear difference in fixations on the Face AOI was observed between children with low SRS scores and with high SRS scores in the ADHD group in the Congruent condition.

In Table S3, the Supplementary Material shows the differences using an ordered factor difference smooth for SRS-Scores. For example, as seen in Table S3, there was no statistical significance between groups in both conditions for all AOIs. Similarly, difference plots in Figure S3 of the Supplementary Material showed that there was no significant difference between groups.

Discussion

In the current study, autistic traits, RJA abilities, and face scanning patterns of children with ADHD were investigated and compared with their TD peers. Additionally, the interaction between autistic traits and the direction of visual attention to objects and faces including the eye and mouth regions were determined in both groups.

We began with the first hypothesis that the SRS scores would be different between children with ADHD and TD children. As a result, it was shown in our research findings that children with ADHD had higher autistic traits compared to their TD peers, which was in line with previous studies that had evaluated autism characteristics through different scales including the Social Communication Questionnaire (SCQ) and Child Behavior Checklist (CBCL) (Kochhar et al., 2011; Kotte et al., 2013; Martin et al., 2014; Reiersen et al., 2008). In one instance, our findings were inconsistent with a previous study which showed elevated autistic traits in school-age children with ADHD using SRS (Ayaz et al., 2013). On the contrary, this contradicts the claim that features of autism determined by using The Checklist for Autism Spectrum Disorder (CASD) are less common than expected in ADHD (Mayes et al., 2012). Thus, these conflicting results may be due to the clinical heterogeneity of ADHD (Taurines et al., 2012) as well as the different sensitivity of the measurement instruments (Mayes et al., 2012), although as previously stated, a majority of the scale evaluations provided similar outcomes.

The current results of the eye-tracking experiment which evaluated the RJA, confirmed our second hypothesis, that the ADHD group would have different values of PoF on the object in the videos. Even though, a statistically significant difference was only determined for the latter stages, when compared to the TD peers, children with ADHD did have lower PoF on object regions throughout the second part of the video, which could be interpreted as a failure to observe communication cues (i.e., gaze) as well as less attention of others' interest, namely, RJA deficits (Marotta et al., 2014). Since RJA, which can be considered as the ability to accurately read and respond appropriately to social situations, is essential for effective social interaction (Mundy, 2018), and poorer RJA might explain for social skill deficits in ADHD (Hoza et al., 2005; Nijmeijer et al., 2008). Moreover, lower PoF values may be result of insufficient attention shifting (Türkan et al., 2016) or an inadequacy in sustained attention (Yıldırım Demirdöğen et al., 2022). Our analyses showed that the statistically significant values between the two groups were determined in only the congruent condition toward the end of the video as the object disappeared. This finding could reflect the difficulty to detect changes (Türkan et al., 2016) or to disengage attention from faces (Gui et al., 2020) among the ADHD subjects who preferentially looked to the faces more than the objects in this timeline.

Another finding in our analysis which was not surprising was the notable difference we determined between congruent and incongruent videos when PoF on the object region was lower in the congruent condition than in the incongruent condition within both groups (See Supplementary Material Table S4 & Figure S2). This evidence showed that the object was more interesting to the child if the model's gaze was directed at the object as well, and less interesting if the model gazed elsewhere. A similar congruent effect has been reported in a sample of typically developing school-aged children (Swanson et al., 2013), although a contrary view was presented in a study suggesting that an object which was not cued was perceived as more novel among infants than an object cued by gaze (Reid and Striano, 2005). The current sample included school-age children which was similar to previous research (Swanson et al., 2013), whereas the other aforementioned research (Reid and Striano, 2005) examined the eye gaze of infants. As a result, the differences among the results between these studies may reflect developmental changes. Additionally, the significant difference between congruent and incongruent conditions in whole sample may reflect a rapid processing of socially relevant information, such as the identification of communicative situations, and could provide a basis for the development of attention sharing, social learning and social-cognitive skills (Manzi et al., 2020).

In recent years, researchers have pointed out the preference of looking for faces among ADHD individuals (Gui et al., 2020; Muszkat et al., 2015). Regarding our third hypothesis, we examined the PoFs on the face of models within the experiment videos, including the eye and mouth regions. While comparing the PoF of face, eye, and mouth regions between the two groups, no significant differences were found while the model was looking straight ahead. This finding contrasted with previous research which indicated that children with ADHD spend less time viewing the relevant areas of faces, specifically the eyes and mouths than TD children (Airdrie et al., 2018; Serrano et al., 2018). This discrepancy may be attributed to the diversity of tasks which were performed in eye-tracking experiments. We primarily hypothesized to assess the RJA abilities of children according to the changes over time, and as a result, designed dynamic stimuli in the form of videos. Whereas in previous studies, only affective pictures were presented for the purpose of evaluating facial emotion recognition skills (Airdrie et al., 2018; Serrano et al., 2018). Another reason why we have obtained results that were inconsistent with the existing literature, may be due to the different characteristics of participants between our study and those in previous research. For example, our study included only male school-age children in contrast to other studies which included both genders and multiple adolescent age groups.

Next, when examining the second part of the videos (TW-2), in which a male/female model looked and turned his/her head toward a corner, including both congruent and incongruent conditions, the PoFs on the model's face and eye regions among the ADHD group was higher and tended to increase more over time as compared to their TD peers. This is in line with behavioral genetic research which described longer gaze durations on the face AOI as a developmental endophenotype of ADHD individuals, suggesting that children with weaker attentional control have difficulties shifting their gaze away from the face and/or directing it to another stimuli (Gui et al., 2020). Researchers have also pointed out that the face likely captures the attention more strongly, which may have made it harder for children to disengage and orient to other objects (Colombo et al., 2004). Similar outcomes have been reported in a recent study that found disruptions in the gaze reorienting process among children diagnosed with ADHD (Frick et al., 2022). On the contrary, there was also evidence of a lack attention to faces among children with ADHD demonstrating their difficulties in recognizing emotional expressions (Airdrie et al., 2018; Serrano et al., 2018).

Although ADHD subjects had higher PoFs on the mouth region than their TD peers throughout TW-2, statistical significance was only found in a short time interval of the congruent condition. Nevertheless, this result appears to be similar to a study in which ADHD children focused on the mouth region more than their TD peers (Muszkat et al., 2015). One explanation for this finding may be related to maladaptive face processing in ADHD, which could be considered a difficulty in processing social cues as well as could potentially lead to impairments in social interaction (Frick et al., 2022). Another implication is that considering that the mouth is crucial for more precise information to be shared regarding the distinction between pleasant and unpleasant emotions, ADHD children tend to fixate more when attempting to identify facial emotions; although this was not specifically investigated as emotion recognition (Muszkat et al., 2015).

To test our fourth hypothesis, we examined the interactions between children's SRS scores and PoFs on the object and face AOIs. Although there were no group-based differences in the effect of SRS scores for the object and face (whole face, eyes, and mouths) regions, our results from the interaction analyses clearly showed an inverse association between autistic traits and PoFs directed at the whole face. As a result, it can be concluded that regardless of the ADHD diagnosis, children with autistic characteristics tend to show less interest in the faces of others, which is consistent with previous studies involving children with TD (Swanson et al., 2013) and ASD (Del Bianco et al., 2022; Vacas et al., 2022).

Limitations

The implications of the cross-sectional findings in the current study were limited to concurrent relationships with an ADHD diagnosis, autistic traits, and eye-tracking measures rather than a causal inference. Also, since the current study was conducted with a small clinical sample which consisted of male children with ADHD and their TD peers, our findings cannot be generalized to female ADHD children and/or other populations. Another limitation was that we did not examine associations between eye-tracking metrics and ADHD symptom severity which could explain some of our findings. Additionally, we did not compare eye-tracking measures in different ADHD presentations. Finally, we did not administer an observational measure of autistic traits, and instead the parents' subjective reports were relied on.

Conclusion

To the best of our knowledge, this was the first study to investigate RJA abilities and face scanning patterns in ADHD children using a dynamic eye-tracking task. Time course analysis, which allowed us to discover different trends in responding to the others' interest and directing attention to others' faces, indicated that the RJA abilities of children with ADHD were not as sufficient as of those of TD as well as that ADHD children tended to use different face scanning patterns that can be described as "atypical." The present study findings showed elevated autistic traits in children with ADHD. However, this did not appear to be associated with their RJA abilities and face scanning patterns. Further research involving larger community samples following a longitudinal design are necessary for clarifying factors related to visual attention as well as to investigate the effects of interventions on social competence comprising JA and face scanning in children with ADHD. Moreover, evaluation of the response to treatment should be addressed in the appropriate clinical settings. In conclusion, it seems that the previously mentioned differences during visual attention to social stimuli brought about insufficiencies in social interaction and communication in children with ADHD. As a result, the current study emphasized the importance of evaluation of JA abilities and face scanning patterns of children with ADHD as well as carrying out the appropriate psychosocial interventions focused on enhancing their social competence.

Supplementary material. For supplementary material accompanying this paper visit https://doi.org/10.1017/S095457942300041X

Availability of data and materials. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Authors contribution. All authors conceived of the study, participated in its design and coordination, and drafted the manuscript; RDT also participated in the collection and interpretation of the data and ÖA performed the statistical analysis. All authors read and approved the final manuscript.

Patient consent statement. Written informed consents were obtained from all participants and their parents.

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Conflict of ınterest. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethical approval. This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Ankara University Faculty of Medicine (Approval number: 12-808-18). Informed consent prior to psychiatric assessment was a prerequisite for study inclusion. Confidentiality was assures, and participants were able to withdraw consent or discontinue participation at any time.

Clinical trial registration. N/A.

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