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Age-Related Differences in Eye-Tracking Correlates of Anxiety Symptoms: A Comparative Study of Adolescents and Adults

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Abstract

Objective: This study aimed to investigate age-related differences in eye-tracking parameters associated with anxiety symptoms in adolescents and adults. **Methods**: A total of 36 participants with clinically relevant anxiety symptoms (Generalized Anxiety Disorder-7 [GAD-7] ≥ 10), including 17 adolescents and 19 adults, were enrolled. Eye movements were recorded using a standardized eye-tracking system during smooth pursuit, prosaccade, antisaccade, Go/NoGo, free-viewing, and exploratory eye-movement tasks. Group differences were analyzed using the Mann–Whitney U test and effect sizes were calculated using Cohen's d. Spearman correlation analyses were performed to examine associations between eye-tracking parameters and GAD-7 scores. Age-group differences in these associations were formally evaluated using GAD-7 × age group interaction models with heteroskedasticity-consistent (HC3) standard errors, with Benjamini–Hochberg false discovery rate (FDR) correction applied across 57 eye-tracking parameters. **Results**: Adolescents showed greater smooth pursuit instability than adults. In adolescents, anxiety severity was associated with multiple smooth pursuit, exploratory, prosaccade, and antisaccade measures, with seven associations remaining significant after FDR correction; no associations survived FDR correction in adults. Formal interaction analyses identified four significant age-group differences involving smooth pursuit deviation count, total deviation, antisaccade latency, and leftward peak amplitude (all FDR-adjusted $P < 0.05$). **Conclusions**: Anxiety severity showed age-dependent associations with eye-tracking performance, particularly in smooth pursuit and antisaccade measures. These findings suggest that developmental stage may influence anxiety-related oculomotor patterns.

Keywords: anxiety symptoms; eye tracking; smooth pursuit; antisaccade; adolescence; executive function; biomarker

Anxiety symptoms represent one of the most prevalent mental health concerns worldwide and are characterized by persistent worry, excessive nervousness, heightened vigilance, and impaired attentional control (1). In recent years, the

prevalence of anxiety symptoms has increased among both adolescents and adults, partly due to changes in social environments and lifestyles. Previous studies have demonstrated that anxiety is associated not only with impairments in academic, occupational, and social functioning, but also with cognitive deficits, reduced quality of life, and an increased risk of various psychiatric conditions (2). Traditional assessment of anxiety symptoms primarily relies on self-report questionnaires and clinical interviews. Although these approaches play an essential role in clinical evaluation, they may be influenced by reporting bias and individual differences in self-awareness due to the subjective and fluctuating nature of anxiety symptoms.

In recent years, eye-tracking technology has emerged as a promising tool in the study of a wide range of psychiatric and neurological disorders (3-5). By recording eye-movement responses to visual stimuli, eye tracking provides objective measures of underlying cognitive and neural processes involved in information processing (6). In the field of cognitive impairment research, eye-tracking measures have been used to characterize abnormalities such as slowed information processing and altered fixation patterns in individuals with early cognitive decline. Moreover, eye tracking has shown considerable utility in the investigation of psychiatric disorders (7). For example, individuals with depression often exhibit prolonged fixation durations and reduced gaze flexibility when viewing emotional stimuli (8), whereas patients with post-traumatic stress disorder (PTSD) frequently display avoidance-oriented and unstable eye-movement patterns. These findings suggest that eye-tracking measures may serve as valuable objective markers for the assessment of neuropsychiatric conditions. In addition, eye-tracking technology has been increasingly applied in developmental psychiatry and pediatric neuropsychology. Previous studies have demonstrated its potential utility in the identification and characterization of neurodevelopmental disorders, including autism spectrum disorder (ASD) and attention-deficit/hyperactivity disorder (ADHD) (9, 10). Collectively, these findings highlight the growing role of eye tracking as an objective and non-invasive approach for investigating cognitive and emotional processes across a broad range of clinical populations.

With regard to anxiety research, previous studies have shown that individuals with elevated anxiety levels are more likely to exhibit attentional bias toward threat-related stimuli, heightened vigilance, and avoidance-oriented gaze patterns when processing emotional information (11). Furthermore, abnormalities in eye-movement performance have been reported across several experimental paradigms. In antisaccade tasks, anxious individuals often demonstrate impaired inhibitory control and reduced response accuracy. In Go/NoGo tasks, anxiety has been associated with deficits in response inhibition and executive functioning. Similarly, during smooth pursuit tasks, individuals with higher levels of anxiety frequently exhibit reduced tracking stability and impaired sustained attention. Collectively, these findings provide a theoretical basis for the application of eye-tracking technology in the objective assessment of anxiety symptoms.

Despite the growing body of evidence linking anxiety symptoms to eye-movement abnormalities, most existing studies have focused primarily on adult populations, whereas investigations involving adolescents remain relatively limited. Importantly, adolescents and adults differ substantially in neurodevelopment, cognitive control, and emotional regulation processes (12). Adolescence represents a critical period of brain maturation, during which the prefrontal cortex and related cognitive control networks continue to develop. Consequently, anxiety symptoms of comparable severity may be associated with distinct neurocognitive mechanisms and eye-movement patterns across different developmental stages (13). Previous research has also suggested that the manifestation and underlying mechanisms of anxiety may vary throughout development (14, 15). However, it remains unclear whether anxiety-related eye-movement characteristics differ between adolescents and adults, and which eye-tracking parameters may serve as the most sensitive indicators of anxiety symptoms at different developmental stages.

Therefore, the present study aimed to investigate age-related differences in eye-tracking measures associated with anxiety symptoms in adolescents and adults. By examining multiple eye-movement paradigms, including smooth pursuit,

antisaccade, Go/NoGo, and free-viewing tasks, we sought to identify developmental differences in anxiety-related eye-movement characteristics. The findings may contribute to a better understanding of the neurocognitive mechanisms underlying anxiety across developmental stages and provide potential objective biomarkers for the assessment and individualized intervention of anxiety symptoms.

Methods

Participants

This retrospective cross-sectional study was conducted at the Department of Medical Psychology, No. 905 Hospital of Navy. Clinical records and eye-tracking data collected between Jan 2026 and Jul 2026 were reviewed. Participants were selected from individuals who underwent routine eye-tracking assessments during outpatient visits to the psychology clinic. All participants had received a clinical diagnosis according to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5), established by experienced psychiatrists. Anxiety symptoms were evaluated using the Generalized Anxiety Disorder-7 (GAD-7) scale. To ensure comparability between age groups and focus on individuals with clinically significant anxiety symptoms, only participants with a GAD-7 score ≥10 were included in the final analysis.

Eligible participants were subsequently categorized into two age groups according to their age at assessment: the adolescent group (12–17 years) and the adult group (18–60 years). Inclusion criteria were: (1) DSM-5 diagnosis of an anxiety-related disorder; (2) GAD-7 score ≥10; (3) normal or corrected-to-normal vision; and (4) ability to complete the eye-tracking assessment. Exclusion criteria were: (1) major psychiatric disorders other than anxiety disorders (e.g., schizophrenia spectrum disorders or bipolar disorder); (2) neurological disorders or history of brain injury; (3) substance abuse or dependence; and (4) use of medications known to affect attention, visual processing, or eye movements.

After data screening, a total of 36 participants met the eligibility criteria and were included in the final analysis, comprising 17 adolescents and 19 adults.

Ethical Approval

All methods were carried out in accordance with relevant guidelines and regulations, and the study was approved by the Ethics Committee of No. 905 Hospital of Navy (No. 2026-01). All study procedures were conducted in accordance with the Declaration of Helsinki and relevant ethical standards. Informed consents were obtained from all participants.

Measures

Anxiety assessment

Anxiety severity was evaluated using the Generalized Anxiety Disorder-7 (GAD-7) scale. The GAD-7 is a widely used self-report instrument consisting of seven items assessing the frequency of anxiety symptoms during the previous two weeks（16）. Each item is scored on a 4-point Likert scale ranging from 0 (“not at all”) to 3 (“nearly every day”), yielding a total score ranging from 0 to 21. Higher scores indicate greater anxiety severity. A score of 10 or above is generally considered indicative of clinically significant anxiety symptoms.

Eye-Tracking Assessment

Eye movements were recorded using the EyeKnow Intelligent Eye Movement Analysis and Evaluation System (EK-1, Beijing Zhongke Ruiyi Medical Information Technology Co., Ltd., Beijing, China). The acquisition display consisted of a dual-eye infrared tracking system with a screen resolution of 3664 × 1920 pixels, a refresh rate of 120 Hz, and an infrared sampling frequency of 90 Hz. All assessments were conducted in a quiet testing room under standardized lighting conditions. The EK-1 system has been used in multiple previous clinical studies to assess eye-movement characteristics in adult populations with cognitive impairment, cerebrovascular diseases, movement disorders, and other neurological or neuropsychiatric conditions. These studies have applied the system across a range of eye-tracking paradigms, including fixation, smooth pursuit, prosaccade, antisaccade, and exploratory eye-movement tasks, demonstrating its feasibility for quantifying oculomotor and cognitive-control-related parameters in clinical populations. The accumulated

evidence from these applications provides support for the reliability and clinical applicability of the EK-1 system for quantitative eye-movement assessment **(17-19)**.

Participants were seated comfortably in front of the display device and instructed to maintain a stable head position throughout the assessment. Before testing, a standard nine-point calibration procedure was performed to ensure optimal tracking accuracy. The eye-tracking system identified pupil positions using infrared image-recognition technology and continuously recorded eye movements during task performance. All eye-movement parameters were automatically processed and calculated using the embedded data-analysis module of the eye-tracking system.

Eye-Tracking Paradigms

Participants completed a battery of eye-movement tasks, including smooth pursuit (dual-task), Go/NoGo, prosaccade, antisaccade, free-viewing, and exploratory eye-movement paradigms.

Smooth Pursuit Task

The smooth pursuit task was designed to evaluate sustained visual tracking ability. Participants were instructed to continuously follow a moving target presented on the screen. The target moved at a velocity of 10°/s for a total duration of 15 s with a maximum excursion angle of 20°. Recorded parameters included initiation latency (ms), pursuit velocity (°/s), pursuit acceleration (°/s²), deviation count, total deviation (>4°, °), mean deviation (>4°, °), and eye-opening rate (%). Greater deviation counts and larger deviation amplitudes were considered indicative of poorer pursuit stability.

Go/NoGo Task

The Go/NoGo paradigm was used to assess response inhibition and executive control. Participants were required to respond to designated target stimuli while withholding responses to non-target stimuli. Outcome measures included response accuracy (%), response latency (ms), and reaction time (ms).

Prosaccade Task

The prosaccade task evaluated visually guided saccadic eye movements. Participants were instructed to rapidly shift their gaze toward target stimuli appearing at different screen locations. Parameters included accuracy (%), latency (ms), fastest

completion time (ms), mean completion time (ms), average saccadic velocity (°/s), peak saccadic velocity (°/s), overshoot frequency, undershoot frequency, multi-step saccade frequency, saccadic gain, and maximum saccadic amplitude in the horizontal and vertical directions.

Antisaccade Task

The antisaccade paradigm was used to assess inhibitory control and voluntary saccadic regulation. Participants were instructed to suppress the automatic tendency to look toward a suddenly appearing peripheral target and instead generate a saccade in the opposite direction. Recorded parameters included antisaccade accuracy (%), latency (ms), fastest completion time (ms), mean completion time (ms), error-correction rate (%), correction latency (ms), average saccadic velocity (°/s), peak saccadic velocity (°/s), maximum saccadic amplitude, uncorrected error rate (%), correct-response latency (ms), and error-response latency (ms).

Free-Viewing Task

The free-viewing paradigm assessed spontaneous visual exploration behavior. Participants viewed visual stimuli without specific task instructions. Outcome measures included total saccade count, fixation count, average task completion time (s), and eye-opening rate (%).

Exploratory Eye-Movement Task

Exploratory eye-movement behavior was evaluated using indices generated by the eye-tracking system, including the Number of Eye Fixations (NEF), Responsive Search Score 1 (RSS1), and Responsive Search Score 2 (RSS2). These parameters were used to characterize visual exploration and information-searching behavior during stimulus observation.

Statistical Analysis

All statistical analyses were performed using Python (version 3.12.7; Python Software Foundation, Wilmington, DE, USA) and SPSS (version 26.0). Continuous variables were expressed as mean ± standard deviation (SD), whereas categorical variables were summarized as frequencies and percentages. Group differences between adolescents and adults were examined using the Mann–Whitney U test for

continuous variables and the chi-square test for categorical variables. Effect sizes were quantified using Cohen's *d*.

Associations between eye-tracking parameters and anxiety severity (GAD-7 scores) were evaluated separately in adolescents and adults using Spearman's rank correlation analysis. Correlation coefficients (r) and corresponding two-sided P values were calculated. The Benjamini–Hochberg false discovery rate (FDR) procedure was applied to account for multiple comparisons.

To formally examine whether the associations between anxiety severity and eye-tracking parameters differed by age group, separate linear regression models were fitted for each eligible eye-tracking parameter. Each model included GAD-7 score, age group (0 = adolescents, 1 = adults), and the GAD-7 × age group interaction term. The interaction term was the primary parameter of interest and represented the difference in the GAD-7 slope between adults and adolescents. Heteroskedasticity-consistent (HC3) standard errors and 95% confidence intervals (CIs) were used for statistical inference. Interaction P values were adjusted across the 57 eligible eye-tracking parameters using the Benjamini–Hochberg FDR procedure. Statistical significance was defined as a two-sided $P < 0.05$, with FDR-adjusted $P < 0.05$ considered statistically significant after multiple-comparison correction.

Results

Participant Characteristics

A total of 36 participants with anxiety symptoms (GAD-7 ≥ 10) were included in the final analysis, comprising 17 adolescents and 19 adults. The adolescent group had a mean age of 14.24 ± 2.19 years, whereas the adult group had a mean age of 36.16 ± 13.76 years. The proportion of females was comparable between the two groups (52.9% vs. 52.6%). Mean GAD-7 scores were 13.35 ± 2.40 in adolescents and 15.84 ± 3.92 in adults. Detailed demographic and clinical characteristics are presented in Table 1.

Group Comparisons of Eye-Tracking Parameters

Comparisons of eye-tracking parameters between adolescents and adults revealed significant between-group differences (Table 1). Compared with adults, adolescents showed a larger overlap prosaccade peak amplitude in the downward

direction (19.58 ± 3.14 vs. 16.86 ± 1.30, $p = 0.016$, Cohen's $d = 1.158$), a longer antisaccade mean correction completion time (517.85 ± 239.19 ms vs. 264.67 ± 103.17 ms, $p = 0.018$, Cohen's $d = 1.510$), and a higher overlap prosaccade peak saccadic velocity (599.34 ± 197.34°/s vs. 493.76 ± 112.35°/s, $p = 0.029$, Cohen's $d = 0.668$). Adolescents also demonstrated higher smooth pursuit deviation counts (26.41 ± 19.45 vs. 13.47 ± 12.97, $p = 0.031$, Cohen's $d = 0.792$), greater total smooth pursuit deviation (>4°) (141.65 ± 98.14° vs. 75.89 ± 72.41°, $p = 0.036$, Cohen's $d = 0.769$), and more overlap prosaccade undershoots (1.53 ± 1.37 vs. 0.79 ± 1.51, $p = 0.039$, Cohen's $d = 0.511$).

Table 1. Demographic and key eye-tracking characteristics of adolescents and adults with anxiety symptoms

Variable	Adolescents (n = 17)	Adults (n = 19)	*P*	Effect size (Cohen's *d*)
Demographic characteristics				
Age (years)	14.24 ± 2.19	36.16 ± 13.76	< 0.001	-1.968
Female, n (%)	9 (52.9)	10 (52.6)	1.000†	—
Male, n (%)	8 (47.1)	9 (47.4)		
GAD-7 score	13.35 ± 2.40	15.84 ± 3.92	0.055‡	-0.756
Eye-tracking parameters				
Overlap Prosaccade Peak Amplitude (Down, °)	19.58 ± 3.14	16.86 ± 1.30	0.016	1.158
Antisaccade Mean Correction Completion Time (ms)	517.85 ± 239.19	264.67 ± 103.17	0.018	1.510
Overlap Prosaccade Peak Saccadic Velocity (°/s)	599.34 ± 197.34	493.76 ± 112.35	0.029	0.668
Smooth Pursuit Deviation Count	26.41 ± 19.45	13.47 ± 12.97	0.031	0.792
Smooth Pursuit Total Deviation (>4°, °)	141.65 ± 98.14	75.89 ± 72.41	0.036	0.769
Overlap Prosaccade Undershoot Count	1.53 ± 1.37	0.79 ± 1.51	0.039	0.511

Notes: Data are presented as mean ± standard deviation unless otherwise indicated.

† Fisher's exact test.

‡ Mann–Whitney U test.

Group comparisons of eye-tracking parameters were performed using the Mann–Whitney U test.

Cohen's d values of 0.20, 0.50, and 0.80 indicate small, medium, and large effect sizes, respectively.

Correlations Between Eye-Tracking Parameters and Anxiety Severity Adolescents

In adolescents, anxiety severity was significantly associated with seven eye-tracking parameters after FDR correction (Table 2). Higher GAD-7 scores were associated with shorter antisaccade latency ($r = -0.810$, adjusted $p = 0.005$) and lower smooth pursuit tracking acceleration ($r = -0.723$, adjusted $p = 0.014$), as well as higher RSS1 ($r = 0.753$, adjusted $p = 0.011$), longer overlap prosaccade fastest completion time ($r = 0.747$, adjusted $p = 0.011$), greater overlap prosaccade peak amplitude (left) ($r = 0.669$, adjusted $p = 0.037$), higher smooth pursuit deviation count ($r = 0.637$, adjusted $p = 0.048$), and greater total smooth pursuit deviation (>4°) ($r = 0.637$, adjusted $p = 0.048$).

Table 2. Associations between eye-tracking parameters and anxiety severity (GAD-7 scores) in adolescents

Eye-tracking parameter	*r*	*P*	FDR-adjusted *P*
Antisaccade Latency (ms)	-0.810	< 0.001	0.005
Responsive Search Score 1 (RSS1)	0.753	< 0.001	0.011
Overlap Prosaccade Fastest Completion Time (ms)	0.747	< 0.001	0.011
Smooth Pursuit Tracking Acceleration (°/s²)	-0.723	0.001	0.014
Overlap Prosaccade Peak Amplitude (Left, °)	0.669	0.003	0.037
Smooth Pursuit Deviation Count	0.637	0.006	0.048
Smooth Pursuit Total Deviation (>4°, °)	0.637	0.006	0.048
Antisaccade Accuracy (%)	-0.606	0.010	0.070
Smooth Pursuit Tracking Velocity (°/s)	-0.583	0.014	0.087
Antisaccade Error Response Latency (ms)	-0.780	0.022	0.126
Prosaccade Overshoot Count	-0.535	0.027	0.138
Antisaccade Peak Amplitude (Left, °)	0.497	0.042	0.178

Antisaccade Mean Completion Time (ms)	-0.489	0.046	0.178
Prosaccade Fastest Completion Time (ms)	-0.488	0.047	0.178

Note: Associations were assessed using Spearman's rank correlation analysis. Only parameters with nominal $P < 0.05$ are presented. *P* values were adjusted using the Benjamini–Hochberg false discovery rate procedure. GAD-7, Generalized Anxiety Disorder-7; FDR, false discovery rate.

Adults

In adults, anxiety severity was primarily associated with inhibitory control–related eye-tracking measures (Table 3). GAD-7 scores were negatively correlated with antisaccade accuracy ($r = -0.608$, adjusted $p = 0.326$) and Go/NoGo reaction time ($r = -0.497$, adjusted $p = 0.645$).

Table 3. Associations between eye-tracking parameters and anxiety severity (GAD-7 scores) in adults

Eye-tracking parameter	*r*	*P*	FDR-adjusted *P*
Antisaccade Accuracy (%)	-0.608	0.006	0.326
Go/NoGo Reaction Time (ms)	-0.497	0.030	0.645

Note: Associations were assessed using Spearman's rank correlation analysis. Only parameters with nominal $P < 0.10$ are presented. P values were adjusted using the Benjamini–Hochberg false discovery rate procedure. GAD-7, Generalized Anxiety Disorder-7; FDR, false discovery rate.

Age-Group Differences in Associations Between Anxiety Severity and Eye-Tracking Parameters

To formally examine whether the associations between anxiety severity and eye-tracking parameters differed between adolescents and adults, interaction analyses were performed using linear regression models including GAD-7 score, age group, and the GAD-7 × age group interaction term. Heteroskedasticity-consistent (HC3) standard errors were used for statistical inference, and interaction P values were

adjusted across the 57 eligible eye-tracking parameters using the Benjamini–Hochberg false discovery rate (FDR) procedure.

Four eye-tracking parameters showed significant GAD-7 × age group interaction effects after FDR correction (Table 4). Significant interactions were observed for smooth pursuit deviation count (interaction $\beta = -6.029$, 95% CI: −8.396 to −3.662, $p < 0.001$, FDR-adjusted $p < 0.001$) and smooth pursuit total deviation (>4°) (interaction $\beta = -29.255$, 95% CI: −41.516 to −16.994, $p < 0.001$, FDR-adjusted $p < 0.001$). Significant interactions were also identified for antisaccade latency (interaction $\beta = 27.849$, 95% CI: 10.895 to 44.802, $p = 0.002$, FDR-adjusted $p = 0.040$) and antisaccade peak amplitude in the left direction (interaction $\beta = -2.213$, 95% CI: −3.627 to −0.799, $p = 0.003$, FDR-adjusted $p = 0.045$). Complete interaction results for all 57 eye-tracking parameters are provided in Supplementary Table S1.

The significant interaction effects are illustrated in Figure 1. Age-specific regression patterns were evident for the two smooth pursuit stability measures and the two antisaccade measures, consistent with differential associations between anxiety severity and eye-movement performance across age groups. Figure 2 summarizes the corresponding interaction coefficients and HC3 robust 95% confidence intervals. Overall, the most robust age-related differences in anxiety–eye-tracking associations were observed for smooth pursuit deviation count and total deviation, with additional significant interaction effects involving antisaccade latency and leftward peak amplitude.

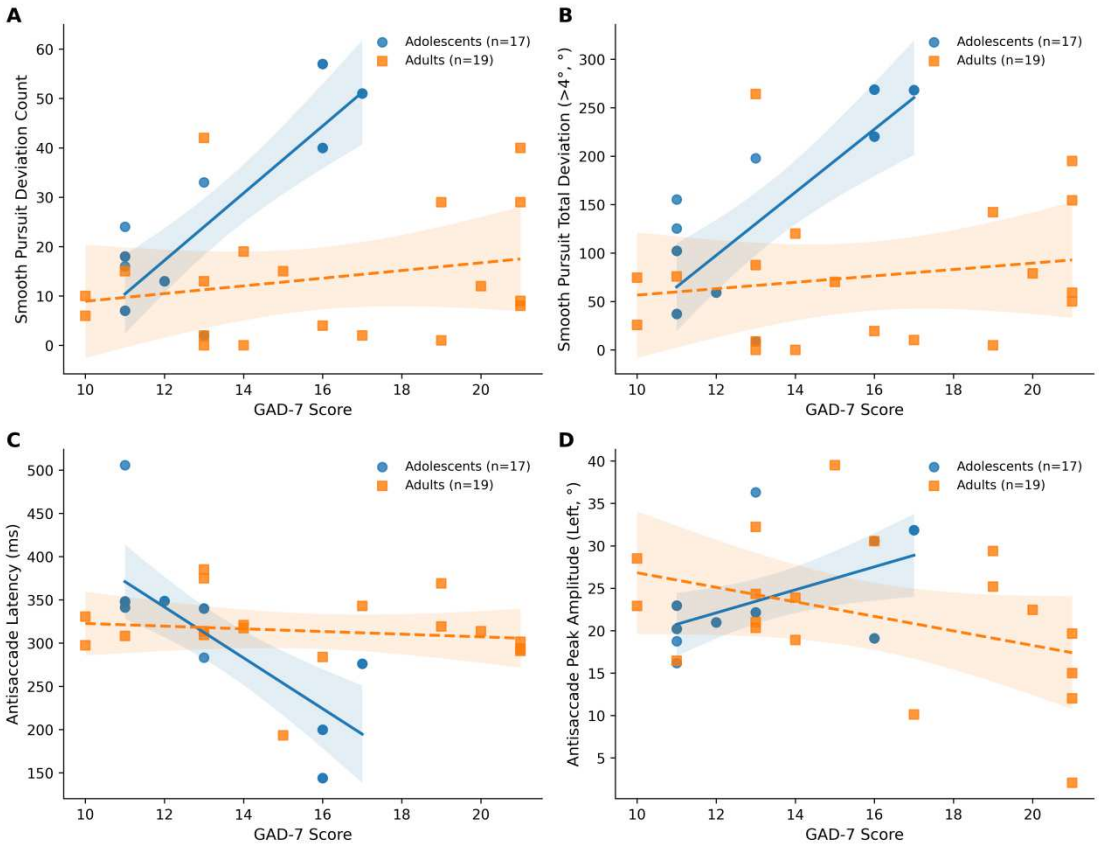
Table 4. Significant age group × anxiety severity interaction effects on eye-tracking parameters

Eye-tracking parameter	N	Interaction *β*	HC3 SE	HC3 95% CI	*P*	FDR-adjusted *P*
Smooth Pursuit Deviation Count	36	−6.029	1.162	−8.396, −3.662	< 0.001	< 0.001

Smooth Pursuit Total Deviation (>4°, °)	36	−29.255	6.019	−41.516, −16.994	< 0.001	< 0.001
Antisaccade Latency (ms)	36	27.849	8.323	10.895, 44.802	0.002	0.04
Antisaccade Peak Amplitude (Left, °)	36	−2.213	0.694	−3.627, −0.799	0.003	0.045

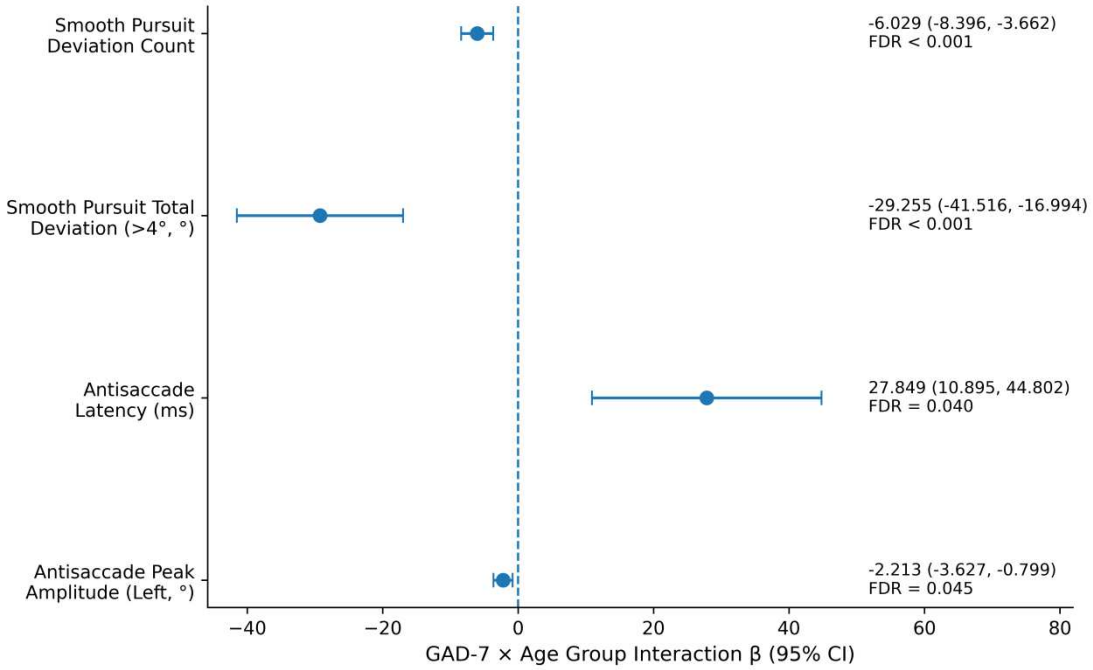
Note: Linear regression models were used to examine whether the associations between anxiety severity and eye-tracking parameters differed between adolescents and adults. Each model included GAD-7 score, age group, and the GAD-7 × age group interaction term. Age group was coded as 0 = adolescents and 1 = adults. Therefore, the interaction coefficient (β) represents the difference in the GAD-7 slope between adults and adolescents (adult slope minus adolescent slope). Heteroskedasticity-consistent (HC3) standard errors were used for statistical inference. *P* values for the interaction term were adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate (FDR) procedure. Only interaction effects that remained significant after FDR correction are presented. β represents the unstandardized regression coefficient. GAD-7, Generalized Anxiety Disorder-7; CI, confidence interval; FDR, false discovery rate.

Figure 1. Age-group differences in the associations between anxiety severity and eye-tracking parameters with significant interaction effects



Note: Scatterplots illustrate the associations between GAD-7 scores and (A) smooth pursuit deviation count, (B) smooth pursuit total deviation (>4°), (C) antisaccade latency, and (D) antisaccade peak amplitude in the left direction in adolescents and adults. Points represent individual participants, and fitted lines represent linear regression trends with 95% confidence intervals within each age group. All four GAD-7 × age group interaction effects remained significant after Benjamini–Hochberg false discovery rate correction. GAD-7, Generalized Anxiety Disorder-7.

Figure 2. Forest plot of significant GAD-7 × age group interaction effects on eye-tracking parameters



Note: The forest plot presents unstandardized interaction coefficients (β) and HC3 robust 95% confidence intervals for eye-tracking parameters showing significant GAD-7 × age group interaction effects after Benjamini–Hochberg false discovery rate correction. Age group was coded as 0 = adolescents and 1 = adults; therefore, the interaction coefficient represents the difference in the GAD-7 slope between adults and adolescents (adult slope minus adolescent slope). Negative coefficients indicate a lower GAD-7-related slope in adults than in adolescents, whereas positive coefficients indicate a higher slope in adults. GAD-7, Generalized Anxiety Disorder-7; HC3, heteroskedasticity-consistent covariance estimator 3.

Discussion

The present study investigated age-related differences in eye-tracking correlates of anxiety symptoms by comparing adolescents and adults with elevated anxiety levels. Several noteworthy findings emerged. First, adolescents demonstrated differences from adults across multiple eye-movement paradigms, particularly in smooth pursuit and overlap prosaccade performance, with several parameters showing

moderate-to-large effect sizes. Second, anxiety severity in adolescents was primarily associated with smooth pursuit and exploratory eye-movement measures, nominal associations in adults were observed for antisaccade accuracy and Go/NoGo reaction time, although these did not remain significant after FDR correction. Third, formal interaction analyses identified significant age-group differences in the associations between anxiety severity and four eye-tracking parameters—smooth pursuit deviation count, smooth pursuit total deviation, antisaccade latency, and leftward antisaccade peak amplitude—and all four interaction effects remained significant after FDR correction.

Compared with adults, adolescents exhibited higher smooth pursuit deviation counts and greater total deviation, as well as differences in several overlap prosaccade parameters, including downward peak amplitude, peak saccadic velocity, and undershoot count. These findings suggest that developmental differences in visual tracking and saccadic control may already be present in adolescents with elevated anxiety symptoms. Although most between-group differences did not remain statistically significant after correction for multiple comparisons, the moderate-to-large effect sizes observed for several parameters indicate potentially meaningful developmental differences that warrant validation in larger cohorts.

More importantly, anxiety severity in adolescents was associated with multiple eye-tracking measures, predominantly involving smooth pursuit performance but also including exploratory eye-movement (RSS1), overlap prosaccade, and antisaccade parameters. Among these, reduced smooth pursuit tracking acceleration and increased tracking deviations showed the strongest associations with anxiety severity. Developmental neuroscience studies have consistently demonstrated that attentional control networks, particularly frontoparietal circuits supporting cognitive control and attentional allocation, continue to mature throughout adolescence (20, 21). As these systems remain under development, anxiety-related interference may disproportionately disrupt the efficient allocation of attentional resources in adolescents. Such disruption may compromise the sustained attention and predictive control required for smooth pursuit, leading to greater tracking instability and

increased pursuit errors (22, 23). In addition, higher anxiety levels were associated with altered overlap prosaccade performance and RSS1, suggesting that anxiety symptoms during adolescence may affect not only sustained visual tracking but also visual exploration and sensorimotor integration.

In contrast, in adults, nominal associations were observed between anxiety severity and antisaccade accuracy and Go/NoGo reaction time, although neither association survived FDR correction. The antisaccade task requires individuals to suppress a reflexive saccade toward a peripheral stimulus and voluntarily generate a saccade in the opposite direction, making it a widely used measure of inhibitory control and executive functioning. The observed negative association between GAD-7 scores and antisaccade accuracy may suggest that adults with more severe anxiety symptoms experience greater difficulty suppressing automatic responses. This finding is broadly consistent with previous studies reporting impaired inhibitory control and executive functioning in individuals with elevated anxiety levels. Similarly, the nominal association between anxiety severity and Go/NoGo performance is consistent with a possible involvement of inhibitory control processes in adult anxiety [14, 15]. However, because neither association remained significant after correction for multiple comparisons, these adult-specific findings should be regarded as exploratory rather than evidence of a distinct adult anxiety-related oculomotor profile.

The formal interaction analyses provided more direct evidence that the associations between anxiety severity and selected eye-tracking measures differed by age group. After FDR correction across 57 eligible eye-tracking parameters, significant GAD-7 × age group interactions remained for smooth pursuit deviation count, smooth pursuit total deviation, antisaccade latency, and leftward antisaccade peak amplitude. The two smooth pursuit deviation measures showed particularly robust interaction effects, with both remaining significant at FDR-adjusted $p < 0.001$. These findings complement the age-stratified correlation analyses by indicating that developmental stage may modify the relationship between anxiety severity and specific aspects of oculomotor performance, particularly smooth pursuit stability and selected antisaccade functions. Importantly, these interaction effects should be

interpreted as differences in the anxiety-related slopes between age groups rather than as simple differences in the overall levels of eye-tracking performance.

The convergence of significant interaction effects in smooth pursuit deviation count and total deviation is noteworthy because both measures reflect tracking stability during continuous visual pursuit. Together with the within-adolescent associations observed for several smooth pursuit measures, these findings suggest that smooth pursuit control may be particularly sensitive to variation in anxiety severity across developmental stages. In parallel, significant interactions for antisaccade latency and leftward peak amplitude indicate that age-related modulation is not restricted to continuous pursuit but may also involve aspects of voluntary saccadic control. Smooth pursuit and antisaccade performance depend on partially distinct but interacting attentional, sensorimotor, and executive-control systems (24, 25), providing a plausible functional context for the observed developmental differences. Nevertheless, the present data do not establish the underlying neural mechanisms, and neurophysiological or neuroimaging studies would be required to determine whether these interaction patterns reflect developmental differences in specific neural circuits.

Several limitations should be acknowledged. First, the sample size was relatively small, particularly in the adolescent group, which may have reduced statistical power and limited the detection of additional group differences. Second, the cross-sectional design precludes causal inferences regarding the relationship between anxiety symptoms and eye-movement abnormalities. Finally, because a relatively large number of eye-tracking parameters were examined, none of the between-group differences remained statistically significant after FDR correction. Accordingly, the present findings should be regarded as hypothesis-generating and require confirmation in larger, adequately powered studies.

Despite these limitations, this study provides preliminary evidence that anxiety symptoms are associated with distinct eye-tracking patterns in adolescents and adults. Anxiety severity in adolescents was primarily related to smooth pursuit dysfunction, whereas anxiety severity in adults was more closely associated with inhibitory control deficits. These findings highlight the potential value of age-specific eye-tracking

indicators in the assessment of anxiety symptoms and provide a basis for future longitudinal and large-scale investigations.

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Authors' contributions

GL: Writing – original draft, Writing – review & editing. YZ: Writing – original draft, Writing – review & editing. TL: Writing – original draft, Writing – review & editing. YW: Writing – original draft. JN: Writing – original draft. YD: Writing – original draft. JW: Writing – original draft. FL: Writing – original draft. TL: Investigation, Writing – original draft, Writing – review & editing.

Availability of data and materials

All relevant data are presented in the text and the tables.

Declarations

Ethics approval and consent to participate

All methods were carried out in accordance with relevant guidelines and regulations, and the study was approved by the Ethics Committee of No. 905 Hospital of Navy (No. 2026-01). All study procedures were conducted in accordance with the Declaration of Helsinki and relevant ethical standards. Informed consents were obtained from all participants.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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