

Visual Attention Dynamics in Children with Special Needs During Eye-Tracking-Based Adaptive Learning Game Sessions in Pontianak, Indonesia

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Abstract

This study aimed to examine changes in oculomotor indicators associated with visual attention across three repeated sessions of an eye-tracking-based adaptive learning game among children with special needs (CSN), addressing the limited evidence on session-to-session visual-attention dynamics in diagnostically heterogeneous populations. An exploratory one-group uncontrolled repeated-measures design was employed involving 16 children aged 9–15 years with mixed diagnoses, including attention-deficit/hyperactivity disorder, autism spectrum conditions, intellectual disability, hearing impairment, and physical disability, recruited from the Disability Services and Assessment Center of Pontianak City. Participants completed three 5-minute game sessions on separate days. Mean fixation duration, saccade count, mean saccade distance, and gaze transition rate were analyzed using the Friedman test, followed by Wilcoxon signed-rank post hoc comparisons with Bonferroni correction ($\alpha = .0167$), while Kendall's W was used to estimate effect size. Saccade count and gaze transition rate differed significantly across sessions ($p = .002$ and $p = .003$, respectively), primarily reflecting a temporary increase during the second session followed by partial reversal in the third session; neither variable differed significantly between the first and third sessions. Mean fixation duration and mean saccade distance increased numerically but were not statistically significant (both $p = .087$). These findings indicate a non-linear oculomotor pattern more consistent with transient exploration or familiarization than sustained improvement in visual attention. The small, heterogeneous, uncontrolled sample limits causal inference and generalizability; future studies should employ larger, diagnostically stratified samples, control conditions, and longer observation periods.

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Introduction

Measuring how visual attention unfolds over repeated exposure to a learning stimulus is a persistent challenge in research on children with special needs (CSN), particularly those with attention-related and neurodevelopmental conditions such as attention-deficit/hyperactivity disorder (ADHD) and autism spectrum disorder (ASD). Because these children often show inconsistent, easily disrupted patterns of sustained gaze, static or single-occasion assessments are poorly suited to capturing how their visual-attentional behavior actually changes when the same stimulus is encountered more than once (American Psychiatric Association, 2022; Barkley, 2015; Chita-Tegmark, 2016).

Attention is a multidimensional cognitive process. It relates not only to how long a person looks at an object, but also to the ability to select relevant stimuli, sustain focus, shift attention, and inhibit responses to distractors (Posner & Petersen, 1990). Eye tracking offers an objective, non-intrusive

way to approximate several of these components through oculomotor indicators—fixation, saccade, gaze duration, and gaze-shift patterns—but these indicators are proxies for attention rather than direct measures of it: their meaning depends on task context, and the same value (e.g., a longer fixation) can reflect either deeper processing or greater difficulty disengaging from a stimulus (Holmqvist et al., 2011; Duchowski, 2017).

Digital, game-based learning environments add a further layer of interest because they can, in principle, be made adaptive: difficulty level, stimulus complexity, and pacing can be adjusted to a learner's responses, a principle known as dynamic difficulty adjustment (Hunicke, 2005; Zohaib, 2018). Games can enhance engagement through feedback, clear goals, and graduated challenge (Plass et al., 2015; Sailer & Homner, 2020), and in special education, serious games have been proposed as a vehicle for attention and cognitive training, provided that difficulty, interface design, and stimulus characteristics are matched to the individual user (Boyle et al., 2016; Wouters et al., 2013). Coupling eye tracking with such a game raises the possibility that gaze behavior itself could, eventually, serve as an input signal for adaptation—though whether a given system actually uses eye-tracking data to drive real-time adaptation, or simply records gaze while the game runs on its own logic, needs to be stated explicitly for any such claim to be evaluated.

Existing eye-tracking research on CSN, however, has concentrated heavily on single-occasion, cross-sectional designs used for screening or for differentiating clinical groups from typically developing peers. A recent systematic review of 14 eye-tracking studies in children with ASD concluded that most available work compares oculomotor strategies between ASD and control groups under highly heterogeneous paradigms and outcome definitions, rather than tracking change within the same individuals over time (Di Cara et al., 2026). Similarly, a review of 74 eye-tracking studies in children and adolescents with ADHD found that the large majority focused on early detection and diagnostic assessment rather than on longitudinal change in visual behavior. Repeated-session designs that could reveal how CSN oculomotor behavior evolves with familiarization, fatigue, and stimulus adaptation therefore remain scarce.

A related and still-developing line of work concerns eye tracking not as an assessment tool but as an intervention modality. A systematic review of eye tracking for rehabilitation and training in paediatric neurodevelopmental disorders concluded that methodologically strong, standardized, and longitudinal designs are still needed to clarify mechanisms and durability of effects (Catalano et al., 2026), and a broader review of gaze-contingent training across brain disorders (1990–2021) reported benefits for cognitive and emotional control but very limited coverage of diagnostically heterogeneous CSN samples. Separately, a large community cohort study found that shorter gaze-fixation duration on social information at age 4 predicted later hyperactivity/inattention symptoms, underscoring that repeated, longitudinal eye-tracking measurement—not a single snapshot—is informative for tracking attentional development (Orui et al., 2025).

This gap motivates the present study. Because CSN visual behavior during technology exposure is not static but can shift with familiarization, fatigue, and session-to-session variation in task difficulty, a repeated-measures design that samples the same children across three sessions of an adaptive learning game can provide a more textured picture of oculomotor dynamics than either a single post-test or a simple pre–post comparison. This study therefore analyzes changes in four oculomotor indicators—mean fixation duration, saccade count, mean saccade distance, and gaze transition rate—across three measurement sessions using an eye-tracking-based adaptive learning

game administered to a group of CSN in Pontianak City, Indonesia. The study is explicitly exploratory and does not test a priori directional hypotheses for the four outcomes; rather, it characterizes the pattern and statistical significance of change over sessions as a basis for future, more tightly controlled work.

Method

Research Design

This study used a quantitative, one-group repeated-measures design, in which the same 16 respondents were measured on three separate days. The design allows each respondent to serve as their own control, reducing between-individual variability, but because no control group or randomization was used, the design is uncontrolled and exploratory: it can describe within-subject change over sessions but cannot, by itself, support causal claims about the effect of the adaptive learning game (Shadish et al., 2002).

Research Setting, Subjects, and Ethical Considerations

The study was conducted at the Disability Services and Assessment Center (LDAC) of Pontianak City, West Kalimantan. The target population comprised children with special needs aged 7–15 years already receiving services at LDAC. Diagnostic or clinical classification (ADHD, ADD, mild ASD, mild intellectual disability, hearing impairment, physical disability) had been established by LDAC's clinical/educational assessment team prior to the study; this study did not re-verify diagnoses independently, which is acknowledged as a limitation below.

Inclusion criteria were: a documented diagnosis of ADHD, mild ASD, or another special need served by LDAC; the ability to follow simple verbal instructions; no severe visual impairment that would preclude eye tracking; and consent from LDAC, the child's school, and the parent/guardian. From an initial pool of 25, 16 children completed all three sessions with usable eye-tracking data; three had finished school, one did not attend school, two participated in the measurements only twice, and three children transferred to other schools, were excluded, or did not complete the protocol. Because comorbidities across diagnostic categories were common in this population, respondents with hearing or physical impairment combined with an attention-relevant diagnosis were retained in the analytic sample but are flagged in the Research Limitations as a source of clinical heterogeneity that this study's sample size could not resolve through subgroup analysis.

This study involved children, a population requiring heightened ethical protection. Ethical approval was obtained from LDAC. Written informed consent was obtained from each child's parent or legal guardian, and age-appropriate verbal assent was obtained from each child before participation; children could discontinue at any point without consequence for their services at LDAC. Institutional permission from LDAC and the child's school was obtained in addition to, and not as a substitute for, this individual consent and assent process.

Measurement Procedure

Each respondent completed three measurement sessions on three separate days, with three consecutive days between sessions. The 5-minute game duration and the three-session schedule were chosen based on Azizah et al. (2026); five minutes was judged sufficient to obtain a stable estimate of the four oculomotor indicators for this population while remaining within these children's tolerance for a single sitting.

Before each session, respondents adjusted their seating position and viewing distance and completed a two-point gaze calibration, during which their eye movements were displayed on screen so they could become familiar with the tracking setup. During the calibration and the subsequent game session, the Tobii Eye Tracker 5 continuously provided gaze-position data to the game through a WebSocket connection. The gaze coordinates were used to identify the screen element currently being viewed and to trigger gaze-based interaction after a predefined dwell time. For levels 1–5, a gaze had to remain on the same target for 500 ms to trigger the corresponding interaction, while level 6 used a shorter dwell time of 200 ms because the target shapes were moving. The experimental display used a 14-inch screen with a resolution of 1366×768 pixels, and the viewing distance was maintained at approximately 45 cm. Lighting and head-position conditions were kept as consistent as practicable across sessions and respondents. Calibration was accepted when the respondent looked at all calibration points displayed in the Tobii application. The provided game implementation does not define an explicit tracking-ratio threshold or an automatic exclusion rule based on excessive data loss; therefore, the tracking-ratio threshold and the number of excluded sessions should be reported based on the actual experimental data-quality procedure rather than inferred from the game code.

The game consisted of several sub-games in which the child's task was to capture a target object (positioned at the top center of the screen) while avoiding distractor objects (other shapes differing from the target object); eye responses were recorded automatically throughout. The system applied the general principle of dynamic difficulty adjustment (Hunicke, 2005; Zohaib, 2018). To make this mechanism reproducible, the operational rules implemented in this study were as follows: the input signal used for adaptation was the participant's game performance, specifically the number of mistakes made while looking at the presented two-dimensional shapes; the decision rule for increasing or decreasing difficulty was making a mistake while looking at a two-dimensional shape more than five times; the discrete difficulty levels available were 1 through 6, where level 5 uses animations and level 6 uses the “catch falling objects” mechanic; and the response window allowed per stimulus was 500 ms for levels 1–5, while a shorter response window of 200 ms was applied at level 6 to accommodate the moving targets. Whether eye-tracking data were used to drive real-time adaptation during this study, or were instead recorded concurrently with a game that adapted on other performance signals, is stated here explicitly: eye-tracking data were recorded concurrently during the game sessions to measure participants' visual behavior, including fixation duration, saccade frequency, saccade distance, and gaze transition rate. These eye-tracking measures were used for subsequent analysis of visual attention and were not used as the direct trigger for real-time changes in game difficulty. The real-time adaptation of difficulty was instead determined by the participant's task performance, particularly the number of mistakes made during the game.

Instruments, Variables, and Operational Definitions

Measurement was performed using a Tobii Eye Tracker 5, with gaze coordinates recorded on a display constrained to 1360×768 pixels. Raw gaze samples (X, Y coordinates and timestamp) were preprocessed prior to event detection: non-numeric or invalid coordinates were removed, records were sorted by timestamp, and duplicate timestamps were dropped.

Fixations were identified using the Identification by Dispersion-Threshold (I-DT) algorithm (Salvucci & Goldberg, 2000), applied with two parameters: a minimum fixation duration of 200 ms and a dispersion threshold of 80 pixels. Beginning at a single gaze point, the algorithm extended the

analysis window until it spanned at least 200 ms, then computed the dispersion of all points in that window as $D = (X_{\max} - X_{\min}) + (Y_{\max} - Y_{\min})$. The window continued to expand as long as D remained at or below 80 pixels; once this threshold was exceeded, the points accumulated up to that point were designated a single fixation. For each fixation, the system recorded its onset and offset time, duration (the timestamp difference between its first and last point), the number of constituent gaze samples, and its centroid coordinates, calculated as the arithmetic mean of the X and Y coordinates of all points in the fixation. The 80-pixel dispersion threshold was set heuristically because eye-to-screen distance, physical monitor size, and visual angle were not recorded for this sample; consequently, fixation classification in this study is anchored to on-screen pixel dispersion rather than to a visual-angle criterion, which is a limitation addressed further below.

Saccades were not detected physiologically via a velocity-based method such as I-VT (Salvucci & Goldberg, 2000); instead, once all fixations in a session were identified, the system connected the centroid of each fixation to the centroid of the next, and each such connection was counted as one gaze transition. Because a sequence of n fixations yields $n - 1$ transitions, the variable reported in this study as “saccade count” is, precisely, the number of inter-fixation gaze transitions ($N_{\text{transition}} = N_{\text{fixation}} - 1$), not a set of saccades verified against a velocity or acceleration profile. This operational choice is noted explicitly here, and the term “saccade” is retained in the Results and Discussion only for consistency with the analysis output and prior draft, with this caveat governing its interpretation throughout (see also Research Limitations).

Four oculomotor indicators were analyzed, using the definitions and formulas above: (1) Mean fixation duration – the average duration (ms) of fixations detected via the I-DT procedure described above. (2) Saccade count – the number of inter-fixation gaze transitions (centroid-to-centroid) detected during the 5-minute session, as defined above. (3) Mean saccade distance – the average Euclidean distance (pixels) between the centroids of consecutive fixations, $d_i = \sqrt{[(C_{x,i+1} - C_{x,i})^2 + (C_{y,i+1} - C_{y,i})^2]}$, averaged across all transitions in the session. Because this value is expressed in on-screen pixels rather than visual angle (viewing distance was not recorded; see above), it is not directly comparable to saccade-amplitude values reported in studies that used visual-angle units, and is reported here in pixels for a 1360×768 px display pending conversion to visual angle in future work. (4) Gaze transition rate – the number of gaze transitions divided by session duration in seconds, $R_{\text{transition}} = N_{\text{transition}} / T$. Because $N_{\text{transition}}$ is the same inter-fixation transition count reported as “saccade count” above, gaze transition rate is not an independent construct but a time-normalized transformation of saccade count (rate = count / 360 s for a 5-minute session); the two indicators are consequently expected to track one another closely within a session, and their parallel pattern of significant change across sessions (see Results and Discussion) is consistent with, rather than independent confirmation of, this shared basis.

Because fixation duration and mean saccade (transition) distance are derived from a different aspect of the same fixation sequence than saccade count and gaze transition rate, the four indicators still capture non-redundant information overall; but the mathematical dependency between saccade count and gaze transition rate should be kept in mind when interpreting the parallel significant results for these two variables in the Results and Discussion below (Holmqvist et al., 2011; Duchowski, 2017). Because the four outcomes were treated as exploratory rather than confirmatory, no a priori directional hypotheses were specified for any indicator; the inferential approach (non-parametric omnibus test per indicator, described below) was chosen accordingly.

Data Processing and Analysis

Data were analyzed using descriptive and inferential statistics. Descriptive analysis reported the mean and standard deviation for each indicator at each of the three measurement sessions.

Because the same 16 respondents were measured three times and the sample size was small, differences across sessions were analyzed for each of the four indicators separately using the Friedman test, a non-parametric test for repeated measures with more than two conditions (Conover, 1999; Field, 2018). Because four separate omnibus tests were run across the four outcomes, findings are interpreted descriptively as an exploratory profile of change rather than as four independent confirmatory tests; readers should weigh the two significant results (saccade count, gaze transition rate) with this multiplicity in mind rather than treating each p-value in isolation.

Where a Friedman test was significant, post hoc pairwise comparisons were conducted using the Wilcoxon signed-rank test, with the significance level Bonferroni-corrected for three comparisons to $\alpha = 0.0167$ (Armstrong, 2014; Field, 2018). Overall effect size for each Friedman test was reported using Kendall's W (Kendall & Babington Smith, 1939; Tomczak & Tomczak, 2014); for each significant pairwise Wilcoxon comparison, a matched-pairs rank-biserial correlation is additionally reported as an effect-size estimate, with 95% confidence intervals where feasible (see Table 3).

Results and Discussion

Result

This section presents the findings in the order of the study's objectives: (1) respondent characteristics, (2) descriptive characteristics of the four oculomotor indicators, (3) differences across the three measurement sessions, and (4) post hoc pairwise comparisons. Results are reported descriptively and supported by tables following APA conventions.

Respondent Characteristics

The study involved 16 children with special needs who had complete data across three eye-tracking measurements. Respondents' ages ranged from 9 to 15 years ($M = 11.1$ years). By sex, 62.5% were male and 37.5% were female.

By diagnosis, the largest group had mild intellectual disability ($n = 6$, 37.5%), followed by ADHD ($n = 4$, 25.0%); two respondents (12.5%) had ADD and two (12.5%) had hearing impairment; one respondent each (6.3%) had mild ASD and physical disability.

This diagnostic heterogeneity means the sample represents several distinct groups of children served at the study site rather than a single clinical population. Because the number of respondents in each diagnostic subgroup was small, formal subgroup analysis was not performed; instead, individual-level trajectories (see Data Processing and Analysis) are used to give an indication of whether the group-level pattern held broadly across diagnoses or was concentrated in particular respondents. Any population-level generalization from this sample should therefore be limited to broadly similar, diagnostically mixed CSN groups rather than to a single diagnostic category.

Characteristics of Visual-Attention Measurements

Table 1. Descriptive statistics of visual-attention indicators by session ($N = 16$)

Indicator	Session 1 Mean $\pm$ SD	Session 2 Mean $\pm$ SD	Session 3 Mean $\pm$ SD
Fixation duration (ms)	494.50 $\pm$ 75.72	541.10 $\pm$ 108.74	564.87 $\pm$ 136.77

Saccade count (times)	129.81 ± 83.31	223.25 ± 99.93	147.69 ± 79.84
Mean saccade distance (px)	273.03 ± 46.66	242.06 ± 32.52	257.24 ± 42.13
Gaze transition rate (times/s)	7.58 ± 2.66	13.68 ± 5.56	9.18 ± 3.72

Among the four indicators, only fixation duration showed a monotonically increasing pattern of group means across sessions (494.50 → 541.10 → 564.87 ms, a 14.2% increase from session 1 to 3), though—as reported below—this trend did not reach statistical significance. Saccade count rose sharply at the second session (129.81 → 223.25, +72%) before falling back toward baseline at the third (147.69). Gaze transition rate followed a similar shape (7.58 → 13.68 → 9.18 times/second). Mean saccade distance moved in the opposite direction at the second session before partially recovering (273.03 → 242.06 → 257.24 px).

Differences in Visual-Attention Indicators Across Sessions

Table 2. Friedman test results for visual-attention indicators across sessions

Indicator	Friedman χ^2	p	Kendall's W	Interpretation
Fixation duration	4.875	0.087	0.152	Not significant
Saccade count	12.000	0.002	0.375	Significant
Mean saccade distance	4.875	0.087	0.152	Not significant
Gaze transition rate	11.375	0.003	0.355	Significant

The Friedman test showed a significant difference across sessions for saccade count, $\chi^2(2) = 12.000$, $p = 0.002$, Kendall's W = 0.375 (medium effect), and for gaze transition rate, $\chi^2(2) = 11.375$, $p = 0.003$, Kendall's W = 0.355 (medium effect). Fixation duration, $\chi^2(2) = 4.875$, $p = 0.087$, and mean saccade distance, $\chi^2(2) = 4.875$, $p = 0.087$, did not differ significantly across sessions.

Post Hoc Analysis

Table 3. Wilcoxon signed-rank post hoc comparisons for significant Friedman tests

Variable	Pair	N	Z	p	Conclusion ($\alpha = .0167$)
Saccade count	P2 vs P1 (14 up / 2 down / 0 tied)	16	-2.741	0.006	Significant
	P3 vs P1 (8 up / 6 down / 2 tied)	16	-1.036	0.300	Not significant
	P3 vs P2 (3 up / 13 down / 0 tied)	16	-2.974	0.003	Significant
Gaze transition rate	P2 vs P1 (14 up / 2 down / 0 tied)	16	-3.051	0.002	Significant
	P3 vs P1 (11 up / 5 down / 0 tied)	16	-1.603	0.109	Not significant
	P3 vs P2 (4 up / 12 down / 0 tied)	16	-2.741	0.006	Significant

Wilcoxon signed-rank comparisons showed that saccade count differed significantly between sessions 1 and 2 ($p = 0.006$) and between sessions 2 and 3 ($p = 0.003$), but not between sessions 1 and 3 ($p = 0.300$). Gaze transition rate showed the same pattern: significant differences between sessions 1 and 2 ($p = 0.002$) and sessions 2 and 3 ($p = 0.006$), but not between sessions 1 and 3 ($p =$

0.109). This session 1-to-3 non-significance is central to how the overall pattern should be read, and it constrains every interpretation offered below: the data support a transient deviation at the second session rather than a monotonic, sustained shift from baseline to endpoint, and this alternative should be kept in view alongside the exploration/familiarization account favored here.

Discussion

Across the three sessions, oculomotor indicators associated with visual attention in this group of children with special needs did not change uniformly. Fixation duration rose gradually but not significantly; saccade count and gaze transition rate rose sharply at the second session and partly reversed by the third, a pattern that was statistically significant for both indicators but was not accompanied by a significant first-to-third difference. Because the significant omnibus effects were driven by this second-session deviation, it would be inaccurate to describe saccade count or gaze transition rate as having “increased across the study”; the more defensible summary is that both indicators changed dynamically across sessions, with the largest deviation occurring at the second session, and any framing of this pattern as sustained improvement is not supported by the data.

A plausible, but unconfirmed, explanation is that the rise in saccades and gaze shifts at session 2 reflects heightened visual-exploration activity as children became more familiar with the device, the seating arrangement, and the game mechanics after an initial, more tentative first session, followed by some combination of fatigue, waning novelty, or motor/oculomotor settling by the third session. This explanation is consistent with the general literature indicating that eye-tracking behavior is sensitive to task familiarity and measurement conditions (Holmqvist et al., 2011), and it is one that a game requiring children to capture moving targets while avoiding distractors would plausibly produce, since more active visual search necessarily involves more gaze shifts. However, this study collected no independent behavioral index—game-performance accuracy, response latency, or similar concurrent measures—that could directly test whether the second-session rise reflects exploration/engagement rather than, for example, increased distractibility or a different oculomotor strategy; it is therefore presented here explicitly as a hypothesis rather than an established finding. Equally plausible competing explanations that this design cannot rule out include task-difficulty changes introduced by the adaptive mechanism itself, differences in stimulus density across sessions, motor-strategy shifts, and the diagnostic composition of the sample (e.g., children with ASD have been reported not to modulate saccade behavior with object familiarity in the way typically developing children do; Wass et al., 2015), any of which could produce a similar transient pattern without implying a common underlying process across respondents.

Fixation duration cannot be interpreted in isolation either. A longer fixation may indicate more sustained visual processing, but it may equally reflect difficulty disengaging from or comprehending the stimulus (Holmqvist et al., 2011; Duchowski, 2017); interpretation therefore needs to be combined with the saccade- and gaze-shift indicators reported alongside it. The relatively short fixation duration observed at the first session ($M = 494.50$ ms) is broadly consistent with prior reports that shorter fixation durations and central-gaze times can characterize children with ADHD relative to typically developing peers, including AI-assisted eye-tracking work reporting an association between higher ADHD symptom scores and shorter fixations (Lee et al., 2023; Chen et al., 2023), and with longitudinal evidence that shorter fixation duration on social information at age 4 predicted later hyperactivity/inattention symptoms (Orui et al., 2025). Read against this literature, the gradual, non-significant increase in fixation duration observed here is a plausible but

unconfirmed signal that may reach significance with more sessions or a larger sample; it should not be treated as evidence of an established training effect.

Before turning to substantive interpretation, an important methodological caveat must be foregrounded: in this study's analysis pipeline, "saccade count" is operationalized as the number of gaze transitions between successive fixation centroids identified via the I-DT algorithm, and "gaze transition rate" is that same transition count divided by session duration—not two independently derived indicators. As a direct arithmetic consequence, the two variables are expected to co-vary tightly within any given session, so the fact that both reached significance with a similar session 1 → 2 → 3 shape (see Method) should be read as one convergent signal about inter-fixation gaze-shift frequency, not as two separate lines of evidence corroborating one another. This also means that "saccade" here refers to a fixation-to-fixation transition rather than a movement verified against a velocity or acceleration profile (e.g., I-VT), so the discussion below of "saccades" should be read with this operational definition in mind rather than as a claim about physiologically classified saccadic eye movements.

With that caveat in place, the pattern of gaze-shift change still needs to be read cautiously against a mixed evidence base that was itself generated using more conventional, often velocity-based, saccade definitions. Some studies report that children with ASD show more saccades than typically developing children or children with ADHD when viewing static images, without the object-familiarity modulation seen in typically developing peers (Guillon et al., 2016), while other, controlled eye-tracking training programs using velocity-based saccade detection over multiple sessions report improvements in saccadic accuracy and inhibitory control in children with ADHD (Lee et al., 2020, 2021; García-Baos et al., 2019). The transient, non-monotonic pattern reported here is therefore consistent with, but does not directly test for, attentional improvement; the contrast with controlled, velocity-based designs underscores why both a control group and a physiologically validated saccade metric are needed before drawing either conclusion. Given the shared derivation of saccade count and gaze transition rate described above, this single gaze-shift-frequency signal, rather than two independent confirmations, is what prior work on gaze-shift rate as a behavioral marker in ADHD screening (Yoo et al., 2024) and on gaze responsiveness to task repetition in longer training programs (Chan et al., 2024) should be compared against.

Mean saccade (inter-fixation transition) distance did not change significantly, decreasing slightly at session 2 before partially recovering at session 3. Combined with the significant change in transition frequency (saccade count/gaze transition rate), this suggests that how often gaze shifted between fixations varied across sessions while the spatial extent of each shift remained comparatively stable—though, because this distance is reported in on-screen pixels rather than visual angle (viewing distance was not recorded; see Method), this comparison cannot be benchmarked directly against saccade-amplitude values from studies using visual-angle units. This interpretation would also benefit from confirmation through Area-of-Interest (AOI), heatmap, or gaze-plot analysis capable of showing whether the additional gaze transitions at session 2 occurred between targets, distractors, or other screen regions (Holmqvist et al., 2011; Duchowski, 2017); such analysis was not performed in this study and is recommended for future work.

This study adds to a small but growing literature on eye-tracking-based games as an assessment and intervention modality for CSN. Systematic reviews in this area have highlighted eye tracking's value as an objective assessment tool across ADHD, ASD, and dyslexia (Shaikh et al., 2026) and have

identified attentional control and executive function—particularly in ADHD—as the domains with the strongest existing evidence for eye-tracking-based training effects on sustained attention, reaction time, and inhibitory control (Catalano et al., 2026). The dynamic, non-linear pattern of change reported here across four indicators is broadly consistent with the direction of that literature, but because this study used a single uncontrolled group, it cannot be interpreted as evidence of a causal intervention effect; other explanations rooted in device/task familiarization, fatigue, motivation, and the diagnostic heterogeneity of the sample remain equally consistent with the data and could not be statistically separated here (Shadish et al., 2002).

Taken together, these findings suggest that an eye-tracking-based adaptive learning game can produce measurable, but multidimensional and non-linear, change in the oculomotor behavior of CSN across sessions, and that no single indicator captures this behavior adequately on its own. For the design of adaptive learning systems, this argues against relying on a single parameter such as fixation duration alone to drive difficulty adjustment; a combination of fixation, saccade, and gaze-transition indicators is likely to give a more complete picture of a user's state, alongside standard considerations of cognitive load, accessibility, and age-appropriate game design (Mayer, 2021; Plass et al., 2015). Any multi-parameter adaptation algorithm implied by this reasoning, however, remains a proposal rather than a demonstrated capability, since this study analyzed each indicator separately and did not test or validate a combined multivariate adaptation rule.

This study has several limitations that should be considered when interpreting the findings. First, the study employed a single-group design without a control condition; therefore, changes in oculomotor indicators cannot be attributed causally to the adaptive learning game. Second, the sample was small ($n = 16$) and diagnostically heterogeneous, which limited statistical power for subgroup comparisons and restricted the generalizability of the findings to any specific diagnostic population; although individual-level trajectories were reported to provide additional descriptive context, diagnosis-specific sensitivity analysis was not feasible. Third, measurements were collected on only three occasions over a relatively short period, preventing conclusions about the durability of observed changes beyond the study window. Fourth, several indicators displayed non-linear patterns driven primarily by the second session, meaning that a simple first-versus-last comparison would inadequately represent the temporal structure of the data; accordingly, the second-session deviation was treated as the principal pattern requiring explanation. Fifth, potentially relevant moderating variables, including diagnosis, age, sex, cognitive ability, prior digital-device experience, and degree of familiarization with the game, were not statistically modeled. Sixth, the study did not include independent behavioral measures of game performance, target accuracy, or response latency, so interpretations related to exploration or engagement remain hypothetical rather than directly tested. Seventh, the variables labeled “saccade count” and “gaze transition rate” were derived from the same inter-fixation transition count identified by the I-DT algorithm, with gaze transition rate calculated by dividing that count by session duration, and therefore should be interpreted as a single convergent indicator of gaze-shift frequency rather than as independent corroborating measures; moreover, their absolute values are not directly comparable with studies using physiologically validated velocity-based approaches such as I-VT. Finally, because eye-to-screen distance and physical monitor dimensions were not recorded, both the 80-pixel fixation-dispersion threshold and the saccade/transition distance metric were expressed in screen pixels rather than

visual angle, which limits direct comparison with studies reporting visual-angle-based thresholds and amplitudes.

Conclusion

Across three sessions of an eye-tracking-based adaptive learning game, children with special needs in this exploratory, uncontrolled study showed significant, non-linear change in saccade count and gaze transition rate—both peaking at the second session before partly reversing by the third—while fixation duration increased gradually and mean saccade distance remained stable, neither reaching statistical significance. This pattern is most consistent with a transient exploration or familiarization phase rather than a sustained, monotonic shift in visual-attentional behavior, and given the small, diagnostically heterogeneous, and uncontrolled sample, the findings are best treated as hypothesis-generating rather than as evidence that the game improved attention.

For future research, a controlled design with randomization, a larger and more diagnostically stratified sample, a longer intervention period, concurrent behavioral (game-performance) measures, and Area-of-Interest or gaze-plot analyses would allow the exploration/familiarization hypothesis proposed here to be tested directly and would clarify whether combining multiple oculomotor indicators rather than relying on any single one—can meaningfully inform the design of adaptive, individually responsive learning systems for this population.

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