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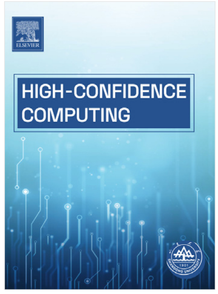

Using virtual reality to enhance attention for autistic spectrum disorder with eye tracking

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Highlights

Using Virtual Reality to Enhance Attention for Autistic Spectrum Disorder with Eye Tracking

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- Heart Rate and Electrodermal Activity showed more sensitivity to attention shifts.
- In the Eye data analysis, the ASD group showed heightened eye openness with Object Opacity and Red Vignette strategies, indicating more attentional focus.
- In the Distraction Log analysis, the 'Noise' and 'Object Opacity' strategies significantly affected attention patterns in both groups across both sessions.
- The 'Red Vignette' strategy demonstrated a significant difference in the ASD group's attention patterns between the two sessions, as revealed in the Distraction Log data.

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Using Virtual Reality to Enhance Attention for Autistic Spectrum Disorder with Eye Tracking

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Abstract

Attention deficit disorder is a frequently observed symptom in individuals with autism spectrum disorder (ASD). This condition can present significant obstacles for those affected, manifesting in challenges such as sustained focus, task completion, and the management of distractions. These issues can impede learning, social interactions, and daily functioning. This complexity of symptoms underscores the need for tailored approaches in both educational and therapeutic settings to support individuals with ASD effectively. In this study, we have expanded upon our initial virtual reality (VR) prototype, originally created for attention therapy, to conduct a detailed statistical analysis. Our objective was to precisely identify and measure any significant differences in attention-related outcomes between sessions and groups. Our study found that heart rate (HR) and electrodermal activity (EDA) were more responsive to attention shifts than temperature. The 'Noise' and 'Score' strategies significantly affected eye openness, with the ASD group showing more responsiveness. The control group had smaller pupil sizes, and the ASD group's pupil size increased notably when switching strategies in Session 1. Distraction log data showed that both 'Noise' and 'Object Opacity' strategies influenced attention patterns, with the 'Red Vignette' strategy showing a significant effect only in the ASD group. The responsiveness of HR and EDA to attention shifts and the changes in pupil size could serve as valuable physiological markers to monitor and guide these interventions. These findings further support evidence that VR has positive implications for helping

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those with ASD, allowing for more tailored personalized interventions with meaningful impact.

Keywords: virtual reality, attention training, autistic spectrum disorders, human-computer interaction

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1. Introduction

ASD is a neurodevelopmental condition primarily marked by challenges in social interaction and communication. While attention issues are frequently observed in individuals with ASD, they are not conventionally considered core diagnostic criteria. However, the impact of attention on ASD is profound, necessitating a deeper understanding and development of strategies to enhance attention in individuals with ASD. Attention is the ability to focus on something while ignoring other things. Individuals with ASD often exhibit a unique attention profile, characterized by difficulties in disengaging and orienting attention, a propensity for overly focused and narrow attention, and a diminished capacity to filter out distractions (53; 57; 54; 55).

These atypical attention patterns are believed to significantly influence the cognitive and behavioral challenges associated with ASD (84; 85). Attention is also integral to the development of higher-level executive functions, further underscoring its importance in this context. Moreover, individuals with ASD display distinct attention behaviors, such as altered sensory responses and a tendency for fixation. Despite these observations, the underlying neural mechanisms remain largely elusive. The difficulties faced by those on the autism spectrum in sustaining attention on externally imposed stimuli underscore the critical need to address attention-related issues in this population. The emphasis on the atypical attention profiles in ASD serves as a gateway to understanding the challenges faced during the transition into adulthood. Notably, as individuals with ASD mature, they continue to encounter difficulties in managing attention, which significantly affects their cognitive functions and ability to discern relationships between sensory stimuli (34; 35). The heightened ability of these individuals to process visual stimuli, a notable strength given their propensity as visual learners, stands in contrast to the impairments in attention that hinder their perception and integration of complex stimuli (36; 37; 35).

Furthermore, individuals with ASD are susceptible to extreme responses due to hyper-reactivity to sensory input, necessitating a simplified interaction

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model to minimize attention demands (38). The correlation between various types of attention and sensory-processing abilities in ASD has been well-documented, with over-arousal to sensory information often coinciding with over-selective attention, a common trait in ASD (36; 33).

Table 1: Different types of Attention

Type of Attention	Description
Focus	Responding discreetly to specific stimuli
Sustained	Ability to maintain focus on one task or stimulus for a long period without getting bored or distracted.
Selective	Continuously focusing on a stimulus in the presence of distracting stimuli
Alternating	Shifting focus between different tasks or stimuli that have different cognitive demands.
Divided	Also known as multi-tasking; Simultaneously responding to different tasks at different levels of cognition.
Joint	Ability to coordinate attention with another person or group in a shared activity, using verbal or nonverbal communication.
Social	Directed towards social stimuli, such as faces or making eye contact.

Building upon this understanding, it becomes clear that attention in ASD is multifaceted, encompassing various types, each with unique characteristics and challenges, as summarized in the table 1. These types of attention are critical in understanding the attention dynamics in ASD. Studies have shown that attention management is critical to the performance of other cognitive functions (e.g., decision-making, memory, problem-solving) and in academic environments, where attention skills are essential for learning and achievement (22; 56). The academic performance of individuals with ASD varies greatly, and the underlying reasons for this diversity remain largely unclear. Although it's well-established that attention is a key predictor of learning outcomes in typically developing individuals, its exact influence on the learning processes of individuals with ASD remains less clear. This uncertainty exists despite the presence of well-documented atypical patterns of attention observed in those with ASD. This variability in educational outcomes, coupled with the recognized importance of attention in learning, underscores the need for further exploration into how attentional abilities might significantly influence the educational achievements of children with ASD, potentially even more than in their typically developing peers (49).

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2. Related Literature

There has been considerable research focusing on the applicability of VR for autism in educational settings, particularly regarding attention and VR's perceived benefits. Visual attention has been extensively investigated in autistic populations, shifting focus from social attention in previous studies (51). Research indicates that two out of five types of attention are consistently targeted for evaluation, with 70% of studies examining sustained attention and 40% focusing on joint attention. It's noteworthy that joint attention deficits are among the earliest indicators of ASD, often targeted in early interventions (1). VR's application in improving joint attention has shown positive results in most cases. For instance, children with neurodevelopmental conditions exhibited significantly longer gazing times on virtual teachers compared to typically developing children (26). However, some studies observed autistic children shifting attention more frequently between non-social objects than between people, underlining the complexity of VR's impact on attention in ASD and ADHD and indicating a need for further research (2).

2.1. Attention Deficits and ASD: A Review of Previous Findings

Building on these observations, previous research has uncovered interesting patterns in ASD and attention. Early detection studies highlight that toddlers at risk for ASD, particularly those later diagnosed, show weaker joint attention skills (45). Additional research has noted difficulties in attention-shifting among individuals with ASD. For example, modifications to a classical spatial cueing task revealed that people with ASD were slower in shifting attention, especially when cues required broader focus (41). Moreover, studies have found that individuals with ASD generally exhibit slower psychomotor and processing speeds compared to typically developing peers, with these speeds being closely correlated with attention-shifting costs, further indicating challenges in controlling visual attention (50).

When investigating sustained attention and working memory, it was found that children with ASD performed worse than children with dyslexia on verbal tests of working memory; sustained attention skills of children with dyslexia were relatively consistent, while there was considerable variability in this skills in children with ASD (42). This variability in sustained attention skills is also supported by Chien (47), who found that young people with ASD showed more inattentive, hyperactive, impulsive symptoms, and performed

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worse on focused and sustained attention. Studies focusing on children diagnosed with both ASD and ADHD revealed they exhibit poorer functional outcomes and responses to treatments, complicating their attention and executive function profiles (40). Another study focusing on a similar topic found that younger individuals with ASD and ADHD are not sufficiently able to sustain attention and/or memory, and that older patients with ASD have difficulty in terms of flexibility. Children with ASD had more trouble with dividing their attention between two things.

Neurological studies have also revealed different aspects of brain functioning in individuals with ASD (46; 48). More insights into ASD's impact on attention revealed that individuals with ASD demonstrated poorer task performance and lower activation in several brain regions, including the inferior prefrontal cortical, medial prefrontal cortical, striato-thalamic, and lateral cerebellar regions. It was also found that individuals with ASD had slower reaction times (43). Those with ASD were reported to exhibit atypical activity in the locus ceruleus, a region of the brain stem that plays a crucial role in modulating brain activity and controlling attention (44). Further subsequent studies revealed that individuals with ASD are susceptible to extreme responses resulting from hyper-reactivity to sensory input (31; 2). It is common for those with ASD to identify as visual learners, such that effective use of visual aids can be critical in fostering attention management and potentially improving academic performance (36).

Given the extensive research highlighting the unique attention challenges in individuals with ASD, VR emerges as a promising tool in this context. As illustrated in Figure 1, a majority of research has focused on utilizing VR to enhance attention, particularly within classroom environments. This growing interest in VR reflects its potential as a versatile and effective means for addressing attention-related difficulties in ASD.

2.2. Development of VR-based Systems

The development of VR-based systems focusing on improving attention is not entirely new, but recent advancements in technology and a deeper understanding of neurodevelopmental conditions have significantly enhanced their potential and application scope.

One of the earliest examples of VR-based attention systems for neurodevelopmental conditions was developed by Cho *et al.* (12). They combined EEG biofeedback and VR technology to create an Attention Enhancement System (AES) for assessing and treating ADHD children, and increasing their

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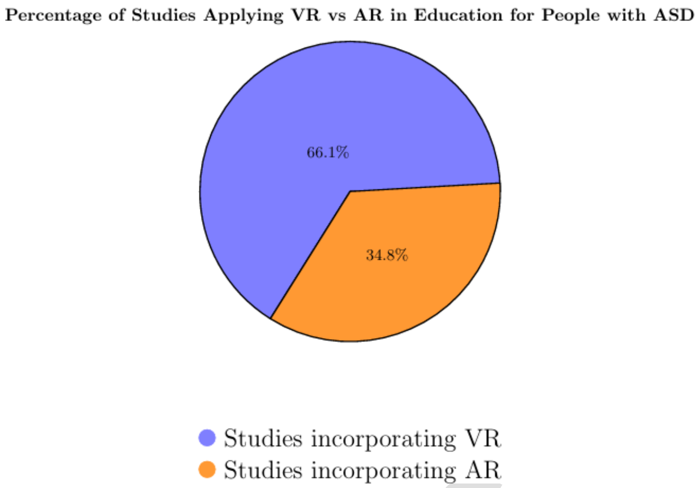

Figure 1: Distribution of VR and AR studies.

attention span. Their VR environment simulated a classroom setting, where they tested 50 subjects aged 14 to 18, who had committed crimes and had been isolated in a reformatory. These subjects had learning difficulties, inattention, impulsivity, hyperactivity, and distractibility. Although they were not officially diagnosed with ADHD, about 30% of them likely had the condition. The subjects were randomly assigned to one of five groups: a control group, two placebo groups, and two experimental groups, each consisting of 10 subjects. The experimental and placebo groups underwent eight sessions of 20 minutes each over two weeks, while the control group received no training. The results showed that the AES was helpful for attention training.

Tan *et al.* (14) also used a VR system to mimic a classroom setting, but they aimed to evaluate and identify ADHD rather than treat it. They employed HTC Vive and other computer devices to create a realistic and interactive 3D VR environment with Unity3D. They also added various distractions, such as students, TV, radio, and street noise, to measure the attention levels of the participants. The system consisted of three modules: data, task, and assessment. The data module stored, sent, and retrieved the cognitive and physiological data of the participants. The task module conducted cognitive tests in VR and collected performance data. The assessment module analyzed the cognitive data in the cloud and diagnosed ADHD. It also used feature extraction and machine learning techniques to comprehensively assess and judge the participants' behavior. One hundred participants participated in the study, and the results indicated that the VR system effectively identified ADHD.

Table 2: Brief Summary of Related Literature using VR for attention improvement

Author(s)	Diagnoses	Overall Outcomes
Cho et al.	ADHD	Using VR EEG Biofeedback and cognitive training improved attention span in children and adolescents with behavioral issues.
Simoes et al.	Autism	Improved cognitive attention of joint attention stimuli.
Chao Mei et al.	Autism	Attention and gaze improved by the innovative therapy, confirmed by autism therapists for future ASD participants.
Chao Mei et al.	Autism	Helped participants gaze less at the irrelevant regions.
Jyoti et al.	Autism	Able to identify joint attention skill deficits.
Vidhusha et al.	Autism	Proved that cognitive ability can be enhanced through constructive teaching by using suitable VR environments.
Tan et al.	ADHD	A system was developed to diagnose ADHD by analyzing a subject's attention level.
Amat et al.	Autism	Children with ASD improved in interpreting gaze -based info, focusing more on the eyes and less on other facial cues.
Sarker et al.	Autism	Proposed game module was effective for both autistic and normal children.
Zhao et al.	Autism	VR-based cognitive training improved typical symptoms of children with ASD
Lu et al.	N/A	Task performances in the autistic group improved by 6.44%

Several studies have developed VR systems specifically for improving attention in autism, yielding successful results (3; 28; 13; 16; 6; 15; 30; 17). Table 2 provides a detailed summary of the outcomes observed in participants with autism. As Table 2 illustrates, participants with autism showed enhanced attention, task performance, and resistance to distraction following VR interventions. This emphasizes the transformative potential of VR as an innovative tool to long-established treatment methods.

2.3. VR Attention Therapy Systems (VRATS) VS Traditional Therapy Methods

Traditional therapy methods for ASD encompass a diverse array of approaches aimed at improving attention. These include Occupational Therapy, which focuses on activities of daily living requiring sustained attention (72), and Physical Therapy, which enhances movement and balance to aid focus and attention. Speech-language therapy is crucial for building skills that

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indirectly improve attention by enhancing the ability to follow instructions and engage in conversations (73). Cognitive-behavioral therapy helps children with ASD understand their feelings and emotions, thus improving attention and focus (15). Additionally, music therapy has shown effectiveness in improving attention as well (67; 68; 69). While effective, the evolution of technology in treatment, especially the use of serious games, has introduced new possibilities for treating ASD. Serious games, often delivered on conventional computers, are specifically designed for children with ASD (61). They bridge traditional methods and advanced technologies like VR and AR. Studies have indicated that these games positively impact executive functions in autistic children, particularly in areas such as imitation skills and working memory. Notably, improvements in attention and concentration have been observed in children after using these cognitive games, though the extent of these effects varies (64).

The incorporation of VR and other advanced approaches into traditional therapies for ASD has yielded significant results. For example, Ryan et al. (62) evaluated the effectiveness of neurofeedback in 132 participants with ASD. They reported that neurofeedback therapy led to moderate improvements in behavioral and emotional challenges, and that neurofeedback alone was more effective than traditional therapies or a combination of both. Tabrizi et al. (63) also found that VR improved memory significantly compared to the control group, and that VR was more effective than medication in both short-term and long-term memory. Lee et al. (73) suggested that VR therapy was a viable option for speech-language disorders, but they noted that most current studies lacked rigorous experimental design.

Interestingly, there is a notable research gap in incorporating VR into some traditional therapies, particularly with Occupational therapy. One notable reason is the lack of comprehensive training programs for occupational therapy practitioners (71). Another potential reason for the gap is likely due to cost. Although VR technology has advanced rapidly, accessibility and cost remain constraints. VR equipment required for therapy may be expensive and not widely available. This can limit the access of individuals with ASD to VR therapy. When examining the most commonly used technologies for occupational therapy interventions for those with ASD, a study revealed that computers and iPads were the most commonly used technologies for OT interventions in individuals with ASD (76). The preference for these devices can be attributed to their lower cost and versatility, which facilitate the integration of additional technologies without straining financial resources.

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Ultimately, this allows for the achievement of therapeutic goals while keeping costs manageable and ensuring the technology remains accessible to a broader range of patients.

Despite these limitations, there do exist some studies that have incorporated VR into occupational therapy for those with ASD, often with positive results (77). At least two other studies had VR-based interventions performed exclusively by an occupational therapist. The duration of the intervention varied from 1 to 8 weeks, with a weekly session of 45 min. Outcomes from both studies revealed that incorporating VR led to both intervention groups achieving better task performance and efficiency (79; 80). When evaluating the impacts of Occupational Therapy-based VR interventions for children with ASD, it was found that this group demonstrated a significant increase in social communication skills and interactions with peers after the intervention (81).

Comparing the two methodologies, it is apparent they offer meaningful benefits to those with ASD. With VR, it is beneficial in reducing cognitive issues. However, there are several limitations that could hinder their effectiveness. These include problems with the size of the software, the physical weight of the devices, the risk of potential addiction, challenges faced by individuals with ASD, particularly children, in tolerating glasses or headsets, and the risk of eye injury (65). In contrast, traditional therapies are well-established and have a solid evidence base supporting their effectiveness in improving communication, social skills, and behavior in individuals with ASD. However, conventional therapeutic approaches can be time-consuming, often requiring intensive, long-term commitment, and may not be as engaging for some individuals, potentially leading to reduced motivation. Furthermore, traditional therapies can sometimes be rigid and may not cater to the unique interests or sensory sensitivities of each individual with ASD. As such, it is imperative that more efforts be made to incorporate VR into some of these traditional therapies to better help those with ASD (82).

3. Experiment Set up and Procedure

The study involved 50 participants aged 17-24, divided into two groups: a condition group comprised of students with ASD and a control group consisting of students without any mental conditions, referred to hereafter simply as the control group. The groups, each with 25 individuals, were further subdivided into five subgroups to implement specific training strategies for attention training, with one subgroup in each serving as a control.

The experimental setup was a VR classroom, meticulously designed to emulate a real classroom environment, complete with essential elements like desks, a clock, a teacher's desk, and whiteboards. The technical configuration included an Alienware desktop and an HTC VIVE Eye Pro headset, which offered high-precision eye-tracking capabilities. An E4 Empatica wristband was used to monitor heart rate, electrodermal activity, and temperature. The Unity Game Engine 2021.3.2f1 was employed to create VR animations, enhancing the realism of the environment.

The core of our experimental procedure involved three distinct sessions: Session 1 serving as a baseline, Session 2 for attention training, and Session 3 for evaluating performance. During these sessions, participants remained seated and experienced various strategies integrated into the VR environment, aimed at manipulating attention and engagement. Each strategy was carefully designed to either serve as a positive or negative reinforcement, or as a form of punishment, to subtly influence participant focus. The strategies are briefly explained below:

- **Scoring**: A reward-based system where participants' scores increased with active engagement in the class, remaining static during periods of inactivity.
- **Vignette**: Implemented as indirect discouragement, a red vignette increased in intensity when a participant's attention waned and decreased in opacity with attentive behavior.
- **Noise**: As an audio-based deterrent, background noise levels escalated with participant distraction and decreased as the focus was redirected to the class.
- **Opacity**: This strategy reduced the visibility of distracting elements (except the teacher) by diminishing their opacity when the participant looked at them, thus encouraging focus on the class.

More detailed information regarding the experiment can be found in (58).

4. Analysis and Results

For this work, the ASD group is of interest. The retrieved data corresponds to a 15-minute trial, which we divided into three sessions, each

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lasting five minutes. For the analysis, session 1 and session 3 data for each participant are considered.

4.1. Physiological Data Analysis

For the HR, EDA, and TEMP data, we used Cohen's D to measure effect sizes. The results are shown in Table 3 and Table 4.

Table 3: Session 1 VS Session 3 Results for Cohen's D

Session 1 VS Session 3	**Cohen's D**
HR	0.45
Temp	0.01
EDA	0.35

Table 4: Cohen's D for ASD and control Groups

Metric	**ASD-Session1**	**ASD-Session3**	**control-Session1**	**control-Session3**
HR	0.30	0.35	0.23	0.10
Temp	0.01	0.02	0.03	0.04
EDA	0.20	0.27	0.18	0.09

In Table 3, the Cohen's D values for HR, Temp, and EDA are compared between Session 1 and Session 3. Examining these values, they indicate that there is a medium effect size for HR (0.45) and EDA (0.35), and a very small effect size for Temp (0.01). This means that there are some differences in HR and EDA between the two sessions, while the difference in Temp is negligible.

In Table 4, the Cohen's D values for HR, Temp, and EDA are compared between Session 1 and Session 3 for two groups: ASD and control. For both groups, the effect sizes for HR and EDA are larger than for Temp, indicating that there are some differences in HR and EDA between the two sessions for both groups. The effect size for Temp is very small for both groups, suggesting that the difference in Temp between the two sessions is negligible. What we can infer from 4 is the following:

- The ASD group had a higher electrodermal activity than the control group.
- The ASD group also had a higher heart rate than the control group.

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Overall, The effect sizes for HR and EDA increased from Session 1 to Session 3 for both groups, but more so for the ASD group. This suggests that the VR intervention had a greater impact on the physiological arousal of the ASD group than the control group over time. The higher electrodermal activity and heart rate in the ASD group indicates higher levels of stress, arousal, or emotional reactivity than the control group. This is consistent with previous research that suggests individuals with ASD have altered autonomic nervous system functioning and higher physiological responses to stimuli (74).

4.2. Eye Log data

The eye log data consisted of measurements pertaining to the current session, current Frame (time - measured in seconds), Left and Right eye Gaze Origins, Left and Right Eye Openness, and Left and Right Eye Pupil Position.

4.2.1. Eye Logs Preprocessing and Data Handling

For ease of access and reference for analysis, the Eye log files were reorganized into separate directories for both groups.

Several steps were taken to clean and preprocess the data. By normalizing the time to a standardized 300-second scale for each session, we effectively aligned the temporal dimension across all records. Then strategy mapping and time mapping were performed. Average pupil sizes and eye openness were calculated by strategy and group.

4.2.2. Eye Logs Analysis

For the analysis of eye log data, we began by compiling basic statistics, as detailed in Table 5. The mean, representing the average value of our dataset, offers insight into the typical measurements of eye openness and pupil size for each group in each session. This is crucial for understanding the general trends within our data. The standard deviation, on the other hand, illustrates the spread of these measurements. A higher standard deviation signifies a wider range of values, indicating more significant variability in eye openness or pupil size within a group or session. Conversely, a lower standard deviation suggests that the measurements are more tightly clustered around the mean, reflecting greater consistency. Together, these metrics provide a foundational understanding of the variations and typical values in eye behavior among the groups across different sessions. When examining table 5, we can see that

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the control group's standard deviation for Average Eye Openness was higher for both sessions 1 and 3. Standard deviations for pupil size were higher in the ASD group than in the control group, suggesting more variability within that group.

Table 5: Group Comparisons for Average Eye Openness and Pupil Size

Group	**Session**	**Average Eye Openness**			**Average Pupil Size**		
		Mean	Median	Std	Mean	Median	Std
ASD	1	0.52	0.51	0.23	4.36	4.58	0.90
ASD	3	0.50	0.50	0.20	4.90	4.99	0.83
control	1	0.54	0.53	0.23	3.83	3.80	0.80
control	3	0.54	0.53	0.23	3.78	3.73	0.81

After computing the basic statistics, we did the following: a 3-way ANOVA, Tukey HSD test, Mann-Whitney U test (In terms of sessions 1 and 3, then another one was done that considered strategy. Two different alphas were also tested to see if the results were consistent.), Rank Biserial Correlation- both for sessions across groups and in terms of strategies. We also tested for stationarity via the ADFuller test. ARIMA was also used for analysis. Both ANOVA and ARIMA are time series analysis methods. Table 6 presents the results of a 3-way ANOVA test, with different p-values to see if results would change. The inclusion of Table 6 in our analysis serves to provide a high-level overview of the data collected in our study, focusing on the variations observed across different strategies, sessions, and groups. The dependent variables under consideration in this table are Average Eye Openness and Average Pupil Size. These are assessed in relation to the independent categorical variables: Current Session, Group, and Strategy.

Judging by Table 6's results, changing the different alphas did not change the results by much. However, we can still gain some insights from this. For Average Eye Openness, the Strategy has a very low p-value, suggesting that the strategy used had a significant impact on eye openness. The cThe current Session also has a significant impact, but less so than strategy. The group has a significant impact with a very low p-value, indicating that there is a significant difference between the ASD and control groups. Furthermore, large F-values for strategy and group suggest that these factors explain a significant amount of variance in both eye openness and pupil size beyond what would be expected by chance, meaning that the probability of observing these results if the null hypothesis were true (i.e., no effect) is extremely low.

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Table 6: 3-way ANOVA for Average Eye Openness and Average Pupil Size

	sum_sq	**df**	**F**	**PR(>F)**	**p-value**
Average Eye Openness (p=0.05)					
C(Strategy)	91.0	3.0	694.27	0.00e+00	0.05
C(Q(Current Session))	1.78	1.0	40.83	1.66e-10	0.05
C(Group)	57.69	1.0	1319.68	8.53e-289	0.05
Residual	53258.22	1218309.00	NaN	NaN	0.05
Average Pupil Size (p=0.05)					
C(Strategy)	140252.46	3.0	79001.02	0.0	0.05
C(Q(Current Session))	2030.61	1.0	3431.39	0.0	0.05
C(Group)	50163.92	1.0	84768.59	0.0	0.05
Residual	720964.66	1218309.00	NaN	NaN	0.05
Average Eye Openness (p=0.01)					
C(Strategy)	91.05	3.0	694.27	0.00e+00	0.01
C(Q(Current Session))	1.78	1.0	40.82	1.66e-10	0.01
C(Group)	57.69	1.0	1319.68	8.53e-289	0.01
Residual	53258.22	1218309.00	NaN	NaN	0.01
Average Pupil Size (p=0.01)					
C(Strategy)	140252.46	3.0	79001.02	0.0	0.01
C(Q(Current Session))	2030.61	1.0	3431.39	0.0	0.01
C(Group)	50163.92	1.0	84768.59	0.0	0.01
Residual	720964.66	1218309.00	NaN	NaN	0.01

Our results are corroborated by the MANOVA findings presented in Table 7. This table includes several statistical tests which evaluate the combined effect of the independent variables on all dependent measures. Using both ANOVA and MANOVA allows us to isolate individual effects and examine their combined influence, enriching our understanding of the data. The meaning of these statistical tests is briefly described below:

- **Wilks' Lambda**: A measure of variance unexplained by the independent variables. Lower values suggest a more pronounced effect.
- **Pillai's Trace**: Reflects the collective squared correlation between dependent and independent variables. Greater values imply a more potent effect.
- **Hotelling-Lawley Trace**: Similar to Pillai's Trace, but focuses on more significant correlations, highlighting stronger relationships. It requires careful interpretation as it's sensitive to assumption violations.
- **Roy's Greatest Root**: Concentrates on the largest single correlation, offering a focused but less comprehensive view of the effects.

Table 7: Multivariate linear model results

Source	Value	Num DF	Den DF	F Value	Pr > F
Intercept					
Wilks' lambda	0.33	2.00	1218308	1216298.08	0.0000
Pillai's trace	0.66	2.00	1218308	1216298.08	0.0000
Hotelling-Lawley trace	2.00	2.00	1218308	1216298.08	0.0000
Roy's greatest root	2.00	2.00	1218308	1216298.08	0.0000
C(Strategy)					
Wilks' lambda	0.84	6.00	2436616	38106.80	0.0000
Pillai's trace	0.16	6.00	2436618	36389.72	0.0000
Hotelling-Lawley trace	0.20	6.00	1624408	39830.54	0.0000
Roy's greatest root	0.19	3.00	1218309	79002.03	0.0000
C(Q(Current Session))					
Wilks' lambda	0.99	2.00	1218308	1730.06	0.0000
Pillai's trace	0.00	2.00	1218308	1730.06	0.0000
Hotelling-Lawley trace	0.00	2.00	1218308	1730.06	0.0000
Roy's greatest root	0.00	2.00	1218308	1730.06	0.0000
C(Group)					
Wilks' lambda	0.93	2.00	1218308	42871.35	0.0000
Pillai's trace	0.06	2.00	1218308	42871.35	0.0000
Hotelling-Lawley trace	0.07	2.00	1218308	42871.35	0.0000
Roy's greatest root	0.07	2.00	1218308	42871.35	0.0000

All the tests (Wilks' Lambda, Pillai's Trace, Hotelling-Lawley Trace, Roy's Greatest Root) show very low p-values for the factors 'Strategy', 'Current Session', and 'Group', indicating that these factors have a statistically significant impact on the combined dependent variables (Average Eye Openness and Average Pupil Size). This suggests that the strategies used, the session number, and the group membership are all influential in determining eye openness and pupil size. The overall interpretation is that Strategies have a significant and moderate to strong effect on the dependent variables. Session changes show a significant but relatively small impact. The results from the MANOVA analysis suggest the following key points:

- **Significant Impact of Independent Variables**: The independent variables considered in the study (Strategy, Current Session, and Group) have a statistically significant impact on the dependent variables (measures such as Average Eye Openness and Average Pupil Size). This is indicated by the very low p-values (less than 0.01) across all test statistics (Wilks' Lambda, Pillai's Trace, Hotelling-Lawley Trace, and Roy's Greatest Root).

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- **Strong Group Differentiation**: The small values of Wilks' Lambda and the significant values of the other test statistics imply that the groups are well-separated based on the combination of dependent variables. This means that the differences in strategies, session numbers, and group types are not only statistically significant but also practically meaningful in terms of their impact on the dependent variables.

After performing the 3-way ANOVA and MANOVA, we did the Tukey HSD Test. This is a beneficial test after ANOVA analysis since it compares the means of multiple groups and determines which ones are significantly different from each other. ANOVA tests indicate if there is a difference among the groups, but not which ones are different. The Tukey HSD test helps identify the specific groups with a significant difference in their means, while controlling for the error rate arising from multiple comparisons. We performed the Tukey HSD test for both Average Eye Openness and Average Pupil sizes at different p-values. Some of these results include the following:

- Comparing against Noise for both groups in session 1: The mean difference is significant (p-adj = 0.0), indicating that Average Eye Openness is different between the ASD and control groups during Session 1 under the Noise strategy.

- Comparing against Score for both groups in sessions 1 and 3: There was a significant difference in the means between Session 1 and Session 3 for the ASD group under the 'Score' strategy.

- Average Pupil Size was lower for the control group in comparison to ASD.

- There is a significant increase in Average Pupil Size when comparing the Noise to the Object Opacity strategies within the ASD group for Session 1.

The following tests we performed were the Mann-Whitney U test and the RBC (Rank-Biserial Correlation). Considering our small sample size and the high likelihood of our data not following a normal distribution, the Mann-Whitney U test was a suitable choice. When applying the test in terms of the different strategies, most of the results indicated significance. As such, we chose to use the RBC to provide an effect size.

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Table 8: Rank Bisceral Correlation between sessions

Variable	Session	Rank-Biserial Correlation
Average Eye Openness	1	0.04
Average Eye Openness	3	0.08
Average Pupil Size	1	-0.35
Average Pupil Size	3	-0.67

From table 8, we can see that :

- **Average Eye Openness in Session 1 (ASD vs control)**: The rank-biserial correlation of 0.04 indicates a tiny effect size, with a slightly higher rank for eye openness in one group compared to the other in Session 1.
- **Average Eye Openness in Session 3 (ASD vs control)**: The rank-biserial correlation of 0.08 is still relatively small. However, it suggests a slightly more pronounced effect in Session 3 compared to Session 1 for eye openness between the two groups.
- **Average Pupil Size in Session 1 (ASD vs control)**: The negative rank-biserial correlation of -0.35 indicates a medium effect size, with one group having consistently smaller pupil sizes compared to the other in Session 1.
- **Average Pupil Size in Session 3 (ASD vs control)**: The negative rank-biserial correlation of -0.67 is a large effect size, indicating a substantial difference in average pupil sizes between the two groups in Session 3. The negative value suggests that the group with the lower ranks in Session 3 had much smaller pupil sizes compared to the other group.

The data presented in table 8 highlight the distinctions in eye responsiveness between ASD and control groups across different sessions. In summary, the effect sizes for eye openness were small, while those for pupil size were medium to large, especially in Session 3. When considering the different strategies, we obtained the following results as seen in table 9.

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Table 9: Rank-Biserial Correlation across both sessions in terms of strategies

Strategy	Variable	Session	Rank-Biserial Correlation
Noise	Average Eye Openness	1	-0.06
Noise	Average Eye Openness	3	-0.02
Noise	Average Pupil Size	1	-0.31
Noise	Average Pupil Size	3	-0.47
Object opacity	Average Eye Openness	1	0.11
Object opacity	Average Eye Openness	3	0.09
Object opacity	Average Pupil Size	1	-0.33
Object opacity	Average Pupil Size	3	0.09
Score	Average Eye Openness	1	-0.02
Score	Average Eye Openness	3	0.00
Score	Average Pupil Size	1	-0.64
Score	Average Pupil Size	3	-0.58
Red vignette	Average Eye Openness	1	0.22
Red vignette	Average Eye Openness	3	0.10
Red vignette	Average Pupil Size	1	-0.22
Red vignette	Average Pupil Size	3	-0.88

Findings from Table 9 reveal that for the object opacity strategy across both sessions, the ASD group had more eye openness in comparison to the control group. Also, The ASD group had lower pupil size than the control group in session 1, but higher pupil size in session 3. For the Red Vignette strategy, the ASD group demonstrated more eye openness, though this effect was slightly less in session 3. The Noise strategy also significantly reduced pupil size, with more pronounced impact as the sessions progressed. These findings suggest that the strategies influenced the physiological arousal of the participants differently, with the ASD group showing higher eye openness and lower pupil size than the control group under most strategies.

Finally, we implemented ARIMA models for the purpose of analyzing and forecasting the time series patterns present in variables such as Average Eye Openness and Average Pupil Size across different sessions and groups (ASD and control). Before that, we tested our data for stationarity via the ADFuller test, and it passed. When testing for ARIMA Models, we found the following, shown in tables 10 through 12.

The inclusion of Table 10 illustrates the different AIC metric results for both groups across both sessions. The ARIMA model metric AIC considers the goodness of fit and the complexity of the model (in terms of the number

Table 10: Comparison of AIC values for Average Eye Openness and Pupil Size in ASD and control. S1 stands for Session 1 while S3 stands for Session 3.

Parameter	ASD AIC	control AIC	Difference in AIC
S1 - Average Eye Openness	-32999.00	-19099.92	-13899.09
S1 - Average Pupil Size	-154107.75	-137021.11	-17086.64
S3 - Average Eye Openness	-353659.36	-18304.19	-335355.18
S3 - Average Pupil Size	-3874209.44	-116812.30	-3757397.14

of parameters). Thus, the lower the AIC value, the better the model fits the data with a penalty for increasing complexity. In our case, for both session 1's Average Eye Openness and Average Eye Pupil size, the AIC was lower for the ASD group than for the control group. This indicates that the model for the ASD group fits the data much better when considering eye openness and pupil size. Similar findings were found in session 3.

Table 11: ARIMA Results for Average Eye Openness - ASD Group and Control Group.

Parameter	ASD Group	control Group
Dep. Variable	Average Eye Openness	Average Eye Openness
No. Observations	90551	93624
Model	ARIMA(1, 0, 1)	ARIMA(1, 0, 1)
Log Likelihood	16503.50	11505.42
AIC	-32999.03	-23002.85
BIC	-32961.35	-22965.06
HQIC	-32987.52	-22991.34
Coefficients		
const	0.52	0.53
ar.L1	0.96	0.95
ma.L1	-0.80	-0.82
sigma2	0.04	0.05
Statistics		
Ljung-Box (L1) (Q)	138.15	158.12
Jarque-Bera (JB)	466.81	1269.40
Prob(Q)	0.00	0.00
Prob(JB)	0.00	0.00
Heteroskedasticity (H)	1.00	1.04
Skew	-0.06	-0.12
Kurtosis	2.67	2.48

Examining tables 11 and 12, we can see that both models fit well with the data, as indicated by their AIC values. The autoregressive terms in both models are robust, implying that previous values heavily influence current values.

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Table 12: ARIMA Results for Average Pupil Size - ASD Group and Control Group

Parameter	ASD Group	control Group
Dep. Variable	Average Pupil Size	Average Pupil Size
No. Observations	90551	93624
Model	ARIMA(1, 0, 1)	ARIMA(1, 0, 1)
Log Likelihood	77057.87	83261.48
AIC	-154107.75	-166514.97
BIC	-154070.09	-166477.18
HQIC	-154096.27	-166503.47
Coefficients		
const	4.36	3.80
ar.L1	0.99	0.99
ma.L1	-0.08	-0.01
sigma2	0.01	0.01
Statistics		
Ljung-Box (L1) (Q)	0.30	2.64
Jarque-Bera (JB)	4275946.93	30387057.29
Prob(Q)	0.58	0.10
Prob(JB)	0.00	0.00
Heteroskedasticity (H)	2.52	1.31
Skew	0.37	0.55
Kurtosis	36.66	91.25

Regarding the ARIMA models for pupil size in session 1, Both the ASD and control groups show powerful autoregressive effects in their average pupil size, indicating that each observation is closely linked to its previous value. The negative moving average coefficients in both models suggest a slight inverse effect of the previous error on the current value. The AIC values are very low, suggesting that the model fits both groups well. However, the high JB values indicate non-normal distributions of residuals, which is a consideration in interpreting these models. Heteroskedasticity is also present, especially in the ASD group, indicating varying variances over time. Overall, the ARIMA Models fit our data, suggesting good fit and applicability for potential forecasting.

4.3. Distraction log data

The distraction logs record the types and durations of the distractor objects that the participants gazed at. Table 13 shows the format of the distraction log file. The gaze time is a pair of numbers, indicating the time (in seconds) spent on an object in session 1 and session 3, respectively.

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Table 13: General Format of a Distraction Log file

Participant	
Rolled Maps (front left 2)	0.07, 0.16
Front Poster	0.62, 0.13
Rolled Maps (leaning)	1.89, 2.09
(FL) Flower 2	0.37, 0.47

4.3.1. Distraction Logs Preprocessing and Data Handling

After preprocessing and data handling, the resulting data were grouped by object name, and the mean time values for both sessions were calculated for each group. The aggregated data from both groups were merged for a direct comparison of the average time values between the two groups, providing valuable insights into the differences in distraction patterns. Table 14 presents the layout of the merged data.

Table 14: Format of the merged data

Object	**Session 1 Time_ASD**	**Session 3 Time_ASD**	**Session 1 Time_control**	**Session 3 Time_control**
(BL) Flower 1	0.02	0.00	0.00	0.01
(BL) Flower 2	0.02	0.05	0.04	0.02
(BR) Flower 1	0.06	0.00	0.04	0.02
(BR) Flower 2	0.08	0.01	0.01	0.04
(FL) Flower 1	0.05	0.02	0.04	0.01
(FL) Flower 2	0.06	0.04	0.02	0.02
(FR) Flower 1	0.03	0.05	0.01	0.07
(FR) Flower 2	0.06	0.00	0.02	0.04
(FR) Flower 3	0.06	0.03	0.05	0.07
Air Conditioner	0.03	0.04	0.01	0.01

Figures 2 and 3 present the average distraction times across all objects. The orange line presents the ASD and control groups for session 3; the blue line presents the ASD and control groups for session 1.

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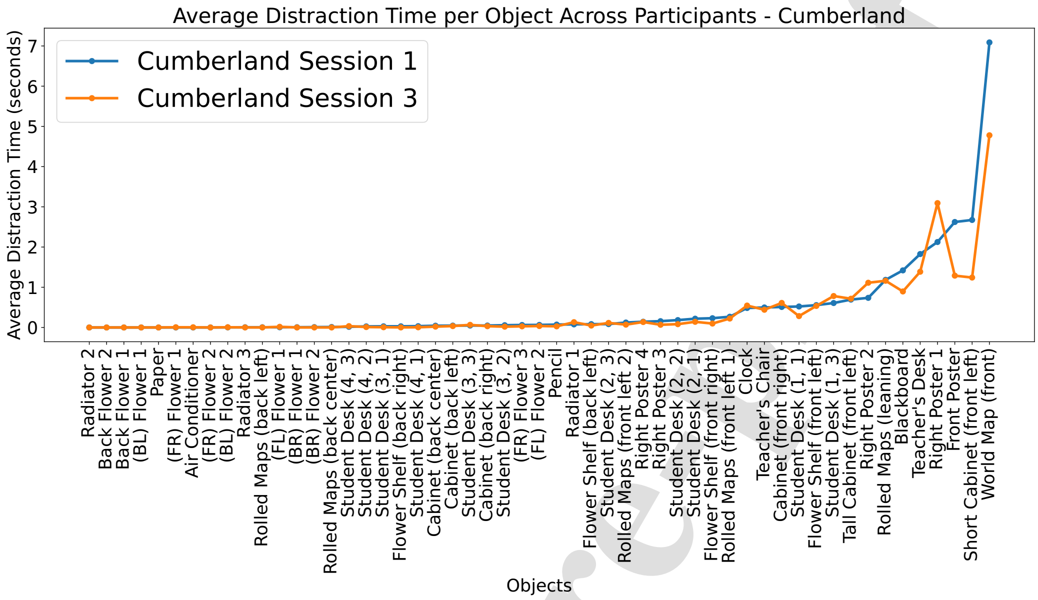

Figure 2: Distraction Time per object in ASD Group

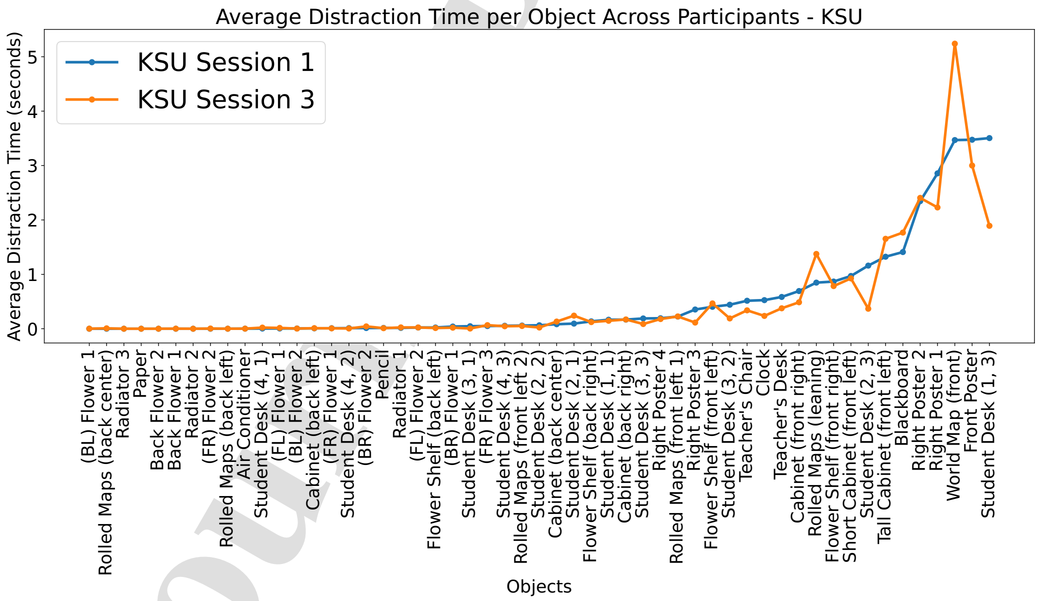

Figure 3: Distraction time per object in control Group

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4.3.2. Distraction Logs Analysis - Session 1 VS Session 3

Next, we used the following methods: Mann-Whitney- U Test, Wilcoxin Signed Ranked Test, and Cohen's D. In this part, we do not consider the strategies used. This part of the analysis was just concerned with finding out whether there was any statistical significance across sessions.

The Mann-Whitney U Test, also known as the Wilcoxon rank-sum test, is a nonparametric statistical test that is used to determine if there are differences between two groups that are not normally distributed. The null hypothesis for this test is that the distributions of both groups are identical, so that there is a 50% probability that a randomly selected value from one population will be greater or less than a randomly selected value from a second population. A p-value less than 0.05 indicates that we can reject the null hypothesis and conclude that there is a statistically significant difference between the two groups.

On the other hand, the Wilcoxon Signed-Rank Test is another nonparametric test that is used to compare two related samples or repeated measurements on a single sample to assess whether their population mean ranks differ. This test is often used when you have 'paired' or 'matched' data, for example, if you measure a group of individuals before and after they undergo a treatment. The null hypothesis for this test is that the median of the paired differences is zero.

The key difference between these two tests lies in the type of samples they are used for. The Mann-Whitney U Test is used for independent samples, while the Wilcoxon Signed-Rank Test is used for related or paired samples. We obtained the following results, as seen in Table 15.

Table 15: Session 1 vs. Session 3 Results for Cohen's D, Wilcoxon Signed Rank, and Mann-Whitney

Results - Session 1 VS Session 3	
Cohen's d Session 1	-0.01
Cohen's d Session 3	-0.04
Wilcoxon Signed-Rank Test - ASD	statistic=296611.0 pvalue=4.3e-14
Wilcoxon Signed-Rank Test - control	statistic=2005311.0 pvalue=7.8e-07
Mann-Whitney U Test Session 1	statistic=16998364.0 pvalue=3.00e-02
Mann-Whitney U Test Session 3	statistic: 16782283.0 pvalue=5.2e-05

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Examining Table 15, the p-values for both ASD and control are significantly less than 0.05, indicating a statistically significant difference in the distributions of the two related groups. Regarding the Mann-Whitney U Test results, A p-value less than 0.05 indicates a statistically significant difference between the two groups. In this case, both Session 1 and Session 3 show significant differences. We also checked for comparison of differences between the two sessions, and the resulting p-value was 0.008, indicating there is a statistically significant difference.

4.3.3. Distraction Analysis - Session 1 VS Session 3 in terms of strategies

In this next part, the strategies are considered in the analysis. Data preprocessing with an additional step of mapping the files from the ASD and control groups to their corresponding strategies was performed.

After obtaining the merged data, we used the same tests as before: Mann Whitney U Tests and Wilcoxin Signed Ranked Tests. Results are shown in Table 16. We also used the Estimated Moving Average (EMA), and implemented ARIMA models.

Table 16: Session 1 VS Session 3 Results in terms of Strategy

Strategy	Tests	Comparison	P Value
Noise	Wilcoxon Signed-Rank	ASD (S1 vs S3)	9.97e-16
	Wilcoxon Signed-Rank	control (S1 vs S3)	8.54e-05
	Mann-Whitney U Test (S1)	ASD vs control	2.98e-09
	Mann-Whitney U Test (S3)	ASD vs control	2.00e-02
Object opacity	Wilcoxon Signed-Rank	ASD (S1 vs S3)	4.00e-04
	Wilcoxon Signed-Rank	control (S1 vs S3)	4.00e-02
	Mann-Whitney U Test (S1)	ASD vs control	5.00e-03
	Mann-Whitney U Test (S3)	ASD vs control	1.90e-01
Score	Wilcoxon Signed-Rank	ASD (S1 vs S3)	1.00e-03
	Wilcoxon Signed-Rank	control (S1 vs S3)	8.69e-06
	Mann-Whitney U Test (S1)	ASD vs control	1.00e-03
	Mann-Whitney U Test (S3)	ASD vs control	7.51e-19
Red vignette	Wilcoxon Signed-Rank	ASD (S1 vs S3)	1.28e-09
	Wilcoxon Signed-Rank	control (S1 vs S3)	4.00e-01
	Mann-Whitney U Test (S1)	ASD vs control	6.45e-17
	Mann-Whitney U Test (S3)	ASD vs control	3.03e-22
No tracking	Wilcoxon Signed-Rank	ASD (S1 vs S3)	3.73e-05
	Wilcoxon Signed-Rank	control (S1 vs S3)	3.75e-06
	Mann-Whitney U Test (S1)	ASD vs control	6.44e-16
	Mann-Whitney U Test (S3)	ASD vs control	2.24e-26

Judging by Table 16, the Noise strategy had a significant effect on the attention patterns of participants in both groups from Session 1 to Session 3. Regarding the Object Opacity strategy, the Wilcoxon Signed-Rank Test shows a significant difference between Session 1 and Session 3 for both groups, indicating that this strategy had an effect on the attention patterns of participants over time. However, the Mann-Whitney U Test shows a significant difference between the two groups only in Session 1, suggesting that this strategy may have had a different impact on the two groups in the first session. Interestingly, with the Red Vignette strategy, Only the ASD group showed a significant difference between the two sessions according to the Wilcoxon Signed-Rank Test, suggesting that this strategy had an effect on the ASD group but not the control group.

We also checked for stationarity, first across both sessions in general, then across both sessions in terms of strategy. As seen in Tables 17 and 18, the ADF statistics for all groups and sessions are significantly negative, and the p-values are very close to 0. Thus, the data for the distraction logs across both groups and strategies for both sessions are stationary.

Table 17: ADF Test Results for Stationarity across both groups and sessions.

Group and Session	**ADF Statistic**	**p-value**
ASD Group - Session 1	-25.76	0.00
ASD Group - Session 3	-9.74	8.41e-17
control Group - Session 1	-12.72	9.79e-24
control Group - Session 3	-13.02	2.40e-24

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Table 18: ADF Test Results for Stationarity across both groups and sessions regarding strategies.

Group - Session - Strategy	ADF Statistic	p-value
ASD Group - Session 1 - Noise	-5.66	9.17e-07
ASD Group - Session 3 - Noise	-9.06	4.53e-15
control Group - Session 1 - Noise	-6.66	4.87e-09
control Group - Session 3 - Noise	-9.05	4.79e-15
ASD Group - Session 1 - Object Opacity	-11.26	1.57e-20
ASD Group - Session 3 - Object Opacity	-14.81	2.00e-27
control Group - Session 1 - Object Opacity	-6.09	1.02e-07
control Group - Session 3 - Object Opacity	-5.98	1.83e-07
ASD Group - Session 1 - Score	-3.84	2.50e-03
ASD Group - Session 3 - Score	-4.20	6.6e-04
control Group - Session 1 - Score	-10.13	9.04e-18
control Group - Session 3 - Score	-15.61	1.74e-28
ASD Group - Session 1 - Red Vignette	-28.91	0.00
ASD Group - Session 3 - Red Vignette	-7.67	1.53e-11
control Group - Session 1 - Red Vignette	-7.13	3.57e-10
control Group - Session 3 - Red Vignette	-6.48	1.27e-08
ASD Group - Session 1 - No Tracking	-23.40	0.00
ASD Group - Session 3 - No Tracking	-4.36	3.5e-04
control Group - Session 1 - No Tracking	-6.43	1.66e-08
control Group - Session 3 - No Tracking	-6.36	2.48e-08

The next steps were to calculate EMA. EMAs are primarily used to identify and confirm trends in time series data. By trying to smooth out short-term fluctuations, EMAs help to reveal the underlying direction of a trend. EMAs can also be used across various time frames - short, medium, or long-term, making them versatile tools for different types of analysis. As seen by Figures 4 and 5, the control group had higher EMAs, but the ASD group had a noticeable peak in Session 3. The ASD group also demonstrated more variability in terms of attention times and strategies.

Figure 6 represents EMA's with respect to time for the ASD and control groups, respectively. The x-axis represents the time in seconds (up to 300 seconds for 5 minutes). The inclusion of these figures represents how attention fluctuated for both groups over the periods of sessions 1 and 3. Examining 6, it is clear that session 1 for the ASD group contained numerous peaks, which indicates periods of fluctuating attention levels. In contrast, session 3 contained less, indicating that the attention levels have become more stable. The ASD group's attention fluctuations for session 3 were higher than the control group's attention fluctuations for that same session.

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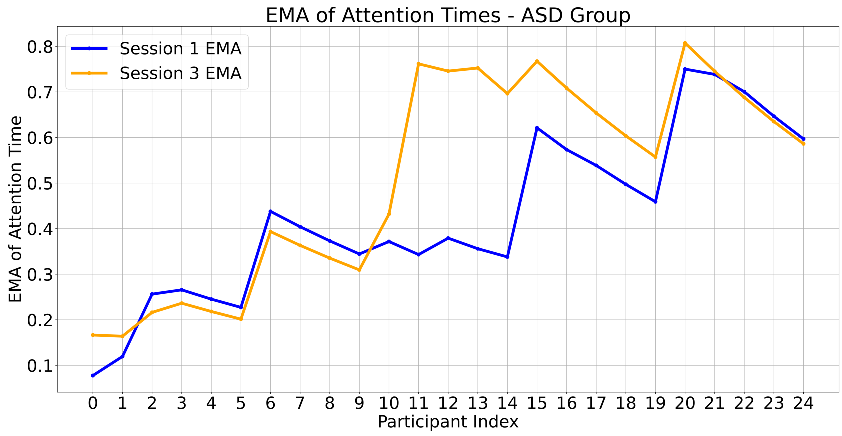

Figure 4: EMAs for participants of the ASD group.

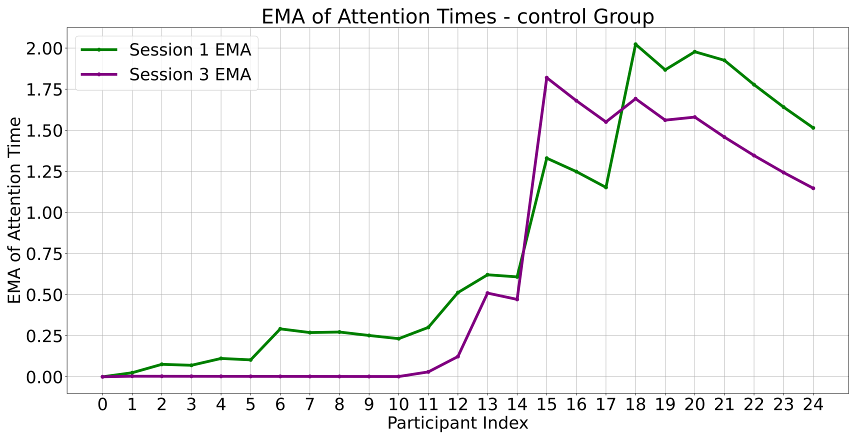

Figure 5: EMAs for participants of the control group.

In figure 7, the control group's attention fluctuations remained relatively consistent, indicating that their attention levels were not substantially influenced by repeated exposure to the VR environment. These findings demonstrate that the VR intervention did have a differential impact on the ASD group's attention patterns, which is valuable information for tailoring future VR-based interventions.

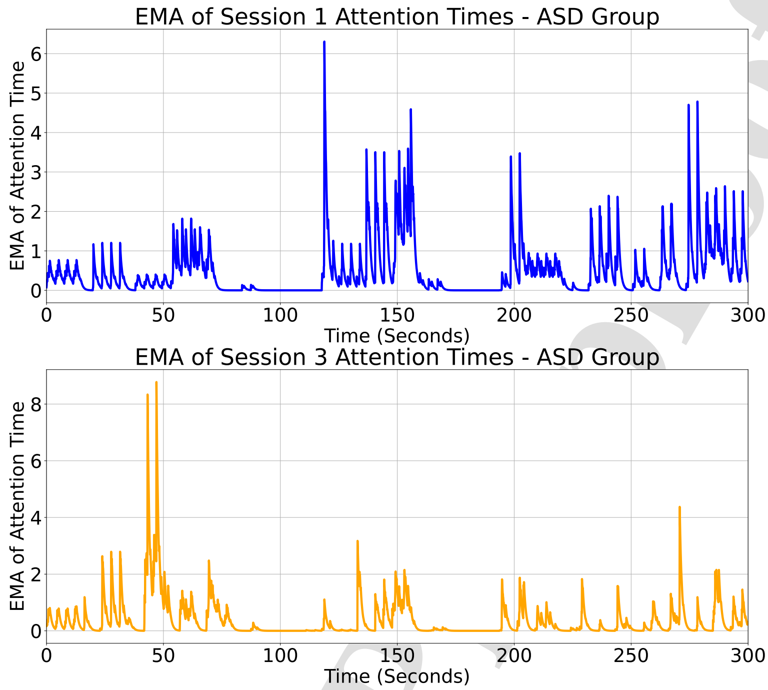

Figure 6: EMA of sessions 1 (top, shown in blue) and 3 (bottom, shown in orange) with respect to time for ASD group

Afterward, ARIMA models were implemented to see any noticeable patterns with regard to strategy. For the distraction log data, upon analyzing the results, we can come to the following conclusions:

- The model fit, as indicated by the log likelihood, AIC, and BIC throughout, varied across strategies and sessions. Generally, the model seemed to fit better for Session 3 data across different strategies, which could imply that the patterns in Session 3 are more stable or predictable.

- Noise Strategy: The models for the 'Noise' strategy showed a low AIC and BIC in Session 3, suggesting a better fit compared to Session 1.

- Score Strategy: For the 'Score' strategy, the ARIMA models showed a better fit in Session 1 than in Session 3, with lower AIC and BIC values. The models also captured the patterns in the data more effectively in Session 1.

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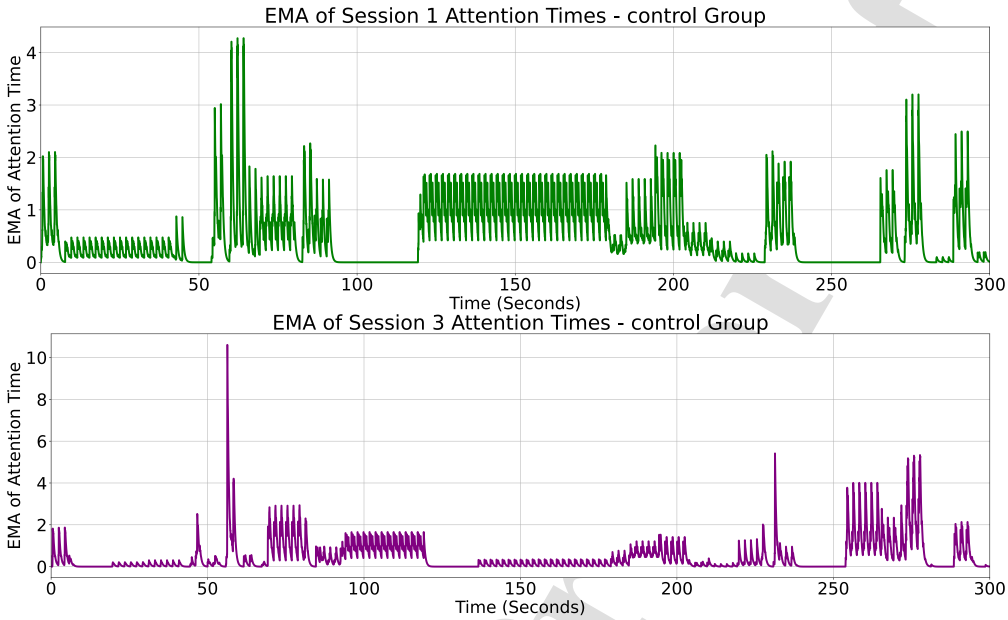

Figure 7: EMA of sessions 1 (top, shown in green) and 3 (bottom, shown in purple) with respect to time for control group

- Red Vignette Strategy: The 'Red Vignette' strategy models showed a large variation between sessions. Session 3 exhibits much lower AIC and BIC values than Session 1, implying a better fit for Session 3 data. However, the coefficients' significance varies between sessions, suggesting different participant behaviors.

5. Conclusion

The integration of ASD, attention management, and VR in our study presents a groundbreaking approach to therapeutic interventions. Our findings underscore the effectiveness of VR as a tool for enhancing attention management in individuals with ASD, highlighting the importance of personalized therapeutic interventions.

Through rigorous time series and statistical analysis, we've confirmed our experiment significantly improved autistic individuals' attention. The marked differences between the first and third sessions strongly validate these results. This not only advances our understanding in this research area but also aids in assessing attentional shifts in individuals with ASD. These findings could be generalizable to assist with other neuro-diverse populations. Significant attention span and quality improvements during VR sessions were observed, indicating that VR's immersive and controlled environments offer unique opportunities for engaging individuals in scenarios that enhance attention management. These improvements were not solely in the duration of attention but also in its quality, with participants demonstrating better focus and less distractibility on relevant tasks.

Our ARIMA model analysis of eye-tracking data collected during VR sessions revealed consistent engagement and appropriate cognitive load among participants. This balance is crucial for effective attention training, as indicated by the Mann-Whitney U tests and rank-biserial correlation results, which showed that our VR interventions were well-tailored to the participants' attentional capacities. The ARIMA model analysis of the distraction log data further corroborates our findings regarding which strategies made the most difference between the two groups.

6. Future Works

Looking forward, we acknowledge that the four-month timeframe of our study might not adequately capture the long-term effects of attention improvements. This realization drives our interest in pursuing more extended intervention periods in subsequent research to more effectively evaluate the enduring impacts of VR-based interventions. Additionally, delving into the complexities of co-morbid disorders, such as the concurrent presence of ASD and ADHD, is of paramount importance. The intricacies of these dual diagnoses present unique challenges and opportunities for VR interventions, particularly in the realm of attention management. While those with ASD have more varied attention profiles, those with ADHD primarily face difficulties in sustaining attention, especially in tasks lacking immediate engagement or reward. They may also exhibit issues with impulse control. The contrast in attentional challenges between ASD and ADHD highlights the need for tailored VR interventions. Such customizations could potentially address the unique attentional profiles of individuals with co-morbid ASD and ADHD, providing invaluable insights and more effective therapeutic strategies. This line of inquiry not only promises to deepen our understanding of attention management in neurodiverse populations but also paves the way for more inclusive and adaptive therapeutic solutions.

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Additionally, future research should also consider extending the scope to include disorders like dementia and other neurodegenerative conditions, where attention management is often compromised. This broadening of scope will not only enhance our understanding of attention management across different conditions but also contribute to the development of more inclusive and effective therapeutic strategies.

In sum, our study highlights the potential of VR as a powerful tool in attention management for individuals with ASD and opens up new avenues for future research. Incorporating artificial intelligence within VR systems could lead to even more personalized and adaptive learning environments, revolutionizing therapy for individuals with ASD and beyond.

Acknowledgement

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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