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Eye Movements and Schizophrenia: A Review on Smooth Pursuit, Saccadic Movements, and Exploratory Eye Movements

Göz Hareketleri ve Şizofreni: Hassas Takip, Sakkadik Hareketler ve Keşfedici Göz Hareketleri Üzerine Bir Derleme

Emine Nur Çorum[1]

[1]Üsküdar University,Istanbul

ABSTRACT

This review article examines the effects of eye movements on smooth pursuit, saccadic movements, and exploratory eye movements in schizophrenia. Eye movements play a critical role in regulating interaction with the visual environment, and schizophrenia significantly alters these processes. Smooth pursuit eye movements enable accurate tracking of an object on the fovea. In individuals with schizophrenia, the eyes often lag behind the target during smooth pursuit, requiring corrective saccadic movements, which indicate difficulties in adapting to the target's speed. Saccadic eye movements refer to rapid, abrupt movements of the eyes. In schizophrenia, impairments are observed in antisaccade and prosaccade tasks. The antisaccade task requires individuals to look in the opposite direction of a distracting stimulus, and high error rates suggest deficits in attention and control mechanisms. In the prosaccade task, individuals are instructed to look toward the distracting stimulus, and people with schizophrenia perform worse compared to healthy individuals. Exploratory eye movements reflect the ability to scan and analyze environmental information. In schizophrenia, these movements are often characterized by shorter scanning paths and fewer fixations, indicating difficulties in processing environmental information. Eye movement abnormalities in schizophrenia show significant differences compared to other disorders and hold potential as biomarkers for diagnosis and treatment. Future research should explore the impact of genetic and neurobiological factors on eye movements and integrate these findings with therapeutic approaches.
Keywords: Eye tracking, schizophrenia, saccadic movements, exploratory eye movements, smooth pursuit

ÖZ

Bu derleme makalesinde şizofrenide göz hareketlerinin hassas takip, sakkadik hareketler ve keşfedici göz hareketleri üzerindeki etkileri incelenmiştir. Göz hareketleri, görsel çevreyle etkileşimin düzenlenmesinde kritik rol oynar ve şizofreni, bu süreçlerde belirgin değişikliklere yol açar. Hassas takip göz hareketleri, bir nesnenin fovea üzerinde doğru bir şekilde izlenmesini sağlar. Şizofreni hastalarında, hassas takip sırasında gözlerin genellikle hedefin gerisinde kalması ve düzeltici sakkadik hareketlerle telafi edilmesi gözlemlenir, bu da hastaların hareket hızına uyum sağlama zorluğuna işaret eder. Sakkadik göz hareketleri, ani ve hızlı göz hareketlerini ifade eder; şizofreni hastalarında antisakkad ve prosakkad görevlerinde bozulmalar görülür. Antisakkad görevinde, çeldirici uyaranın zıt yönüne bakma talimatı verilir ve yüksek hata oranları dikkat ve kontrol mekanizmalarındaki bozuklukları gösterir. Prosakkad görevinde ise, çeldirici uyaranın yönüne bakılması istenir ve şizofreni hastaları bu görevde sağlıklı bireylerden daha düşük performans sergiler. Keşfedici göz hareketleri, çevresel bilgiyi tarama ve analiz etme yeteneğini yansıtır. Şizofreni hastalarında, keşfedici göz hareketleri genellikle daha kısa tarama yolları ve daha az fiksasyon sayısı ile karakterize edilir, bu da çevresel bilgileri işleme zorluklarını gösterir. Şizofrenide göz hareketi bozuklukları, diğer bozukluklarla karşılaştırıldığında anlamlı farklılıklar görülmektedir, bu bozukluklar hastalığın tanı ve tedavisinde potansiyel biyobelirteçler olarak değerlendirilebilir. Gelecekteki araştırmalar, genetik ve nörobiyolojik faktörlerin göz hareketleri üzerindeki etkilerini ve bu bozuklukların tedavi yöntemleriyle birleştirilmesini ele almalıdır.
Anahtar sözcükler: Göz takibi, şizofreni, sakkadik hareketler, keşfedici göz hareketleri, hassas takip

Introduction

Eye movements are complex cognitive processes that regulate and interpret individuals' interactions with their visual surroundings. While human visual acuity is maximized at the central fovea of the retina, it significantly declines in peripheral regions. Therefore, proper alignment of visual objects onto the fovea is essential for accurate and clear visual information acquisition (Morita et al. 2020). In this context, eye movements play a

Address for Correspondence: Enine Nur Çorum, Üsküdar University Institute of Health Sciences, Department of Neuroscience, Istanbul, Türkiye **E-mail:** eminenurfayda@gmail.com
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critical role in reflecting the dynamics of visual perception and are considered a central factor in understanding visual information processing (Blain et al. 2023).

Schizophrenia is a severe mental disorder that typically begins in adolescence and often progresses chronically. It is part of the psychosis spectrum, affecting thought, perception, and behavior, and emerges from the interaction of genetic and environmental factors (Bakhshi and Chance 2015). The clinical symptoms of schizophrenia are generally categorized as positive, negative, and cognitive, significantly impacting individuals' social and functional capacities. Despite these common characteristics, schizophrenia is an extremely heterogeneous disorder, as evidenced by the diverse clinical presentations of patients (Pillinger et al. 2019). Although over a century of research has been conducted, the core processes and causal mechanisms of schizophrenia remain incompletely understood (Chong et al. 2016). Eye movement abnormalities, however, have been recognized in schizophrenia since the early 20th century (Diefendorf and Dodge 1908). Researchers have been inspired by the notion that these abnormalities may offer significant insights into understanding the clinical symptoms and functional impairments associated with the disorder (Gracitelli et al. 2015, Jurišić et al. 2020).

Eye movement abnormalities in schizophrenia are thought to play a more critical role than previously assumed and are reported to manifest in the early stages of the disorder (Gracitelli et al. 2015). In one early study, prominent visual perception impairments were observed in individuals with early-stage schizophrenia even before depressive symptoms developed (Chapman 1966). These findings suggest that visual perception impairments may represent some of the earliest and most pervasive behavioral symptoms of schizophrenia (Ales et al. 2021, Chrobak et al. 2022). Recent studies on the eye movements of individuals with schizophrenia present a broad spectrum of oculomotor changes that support this notion. These abnormalities are often linked to other cognitive and functional impairments (Keane et al. 2018, Morita et al. 2019, Shmukler et al. 2021).

The neurobiology of eye movement abnormalities in schizophrenia has been associated with the roles of neurotransmitters such as dopamine and glutamate. Hypodopaminergic activity in the mesocortical pathway is known to trigger negative symptoms, while hyperdopaminergic activity in the mesolimbic pathway leads to positive symptoms (Jurišić et al. 2020). Alterations in dopamine activity, both decreases and increases, have also been observed in the retinas of individuals with schizophrenia (Silverstein and Rosen 2015). Dopamine deficiency reduces color perception, while excess dopamine enhances perception but diminishes spatial frequency processing. During the acute onset of schizophrenia, dopamine levels increase, returning to normal during remission phases. Consequently, visual impairments during acute psychotic episodes differ from those observed during antipsychotic treatment (Kegeles et al. 2010). Additionally, glutamate has been implicated in the degeneration of retinal ganglion cells, playing a role in the neurodegeneration process (Javitt 2007). Dysregulation of the N-methyl-D-aspartate receptor is known to increase dopamine and glutamate release, exacerbating visual impairments and hallucinations (González-Hernández et al. 2014).

This study aims to conduct a comprehensive review of eye movement abnormalities in schizophrenia, categorized into smooth pursuit, saccadic, and exploratory eye movements. This review contributes to a deeper understanding of the issues arising from bottom-up mechanisms and offers a foundation for new visual-training-centered approaches in the diagnosis and treatment of schizophrenia. A detailed analysis of eye movement abnormalities associated with schizophrenia may enhance the understanding of the neurobiological underpinnings of the disorder and aid in the development of more effective intervention strategies in clinical practice.

Types of Eye Movements

Modern research often categorizes eye movements in schizophrenia into smooth pursuit movements, saccadic movements, and exploratory eye movements (Bey et al. 2019). Smooth pursuit eye movements measure the ability to track moving objects, while saccadic movements refer to sudden and rapid eye movements. Exploratory eye movements, on the other hand, serve the purpose of investigating and exploring environmental stimuli (Holzman et al. 1973, Kojima et al. 1992). The functions of eye movement types are summarized in Table 1.

Saccadic Eye Movements

Saccadic eye movements are defined as rapid, abrupt shifts of the eyes from one point to another, typically occurring with a reaction time of around 200 milliseconds (ms) and lasting between 20 and 120 ms (Ettinger et al. 2005, Luna et al. 2008). These movements can reach speeds of 600–700 degrees/second (°/s) in humans and

can be either voluntary or involuntary. Saccadic movements are characterized by the amplitude-peak velocity relationship and are assessed based on latency and accuracy (Wolf et al. 2021).

Saccades can be categorized into various types, including visually guided saccades (externally triggered reflexive saccades) and internally triggered scanning saccades, antisaccades, memory-guided saccades, and predictive saccades (Broerse et al. 2001). In antisaccade tasks, when a peripheral target is presented, the eyes must move in the opposite direction of the target, requiring the inhibition of the reflexive saccade typically triggered by a visual stimulus (Hutton and Ettinger 2006, Gooding and Basso 2008). Conversely, in reflexive saccade or prosaccade tasks, individuals are instructed to look toward the direction of the distracting stimulus (Ettinger et al. 2006).

Table 1 Types and functions of eye movements

Types of eye movements	Definition	Significance
Smooth Pursuit	The ability to track moving objects	Critical for visual attention and object tracking
Saccadic movements	Sudden and rapid eye movements	Essential for rapid information acquisition and regulation of visual perception
Exploratory eye movements	Exploring and investigating environmental stimuli	Important for gathering and interpreting environmental information

(Holzman et al. 1973, Kojima et al. 1992, Bey et al. 2019)

Smooth Pursuit Eye Movements

The smooth pursuit system differs from the saccadic system as it facilitates the voluntary maintenance of a moving stimulus clearly on the fovea of the retina, enabling accurate tracking of moving objects. For instance, this system allows us to catch a ball approaching at speed or cross a street without moving into the path of a moving vehicle. Unlike the rapid eye movements of the saccadic system, the pursuit system involves slow eye movements (and small corrective saccades) that approximate the speed of the moving target to keep the visual image focused on the fovea. Single-cell and human neuroimaging studies have found that smooth pursuit is supported by regions adjacent to those involved in the saccadic system and overlaps with areas that support the vestibular system, playing a fundamental role in pursuit processes (Fukushima et al. 2006).

Exploratory Eye Movements

Exploratory eye movements reflect individuals' ability to scan environmental visual information and perform perceptual analyses. These movements play a critical role in systematically scanning environmental information and are directly linked to cognitive processes (Morita et al. 2020). The evaluation of exploratory eye movements includes factors such as the number of eye fixations, search response scores, total scan path length, mean scan path length, and discriminative analysis (Miyahira et al. 2000, Suzuki et al. 2009).

Saccadic Eye Movement Abnormalities in Schizophrenia

In recent years, a significant portion of research on psychiatric patient groups has focused on saccadic performance. This interest is driven by the accessibility and non-invasive nature of saccadic movements for investigating psychomotor functions, high-level cognitive processes, and their neural mechanisms. Additionally, the reliable and precise measurement of saccadic eye movements has contributed to an accumulation of knowledge in this field.

The most frequently observed saccadic abnormalities in schizophrenia patients occur in antisaccade tasks (Reuter et al. 2005, Radant et al. 2007, Waters et al. 2012). Antisaccade tasks require inhibitory control and adherence to task instructions (Bey et al. 2019). Increased antisaccade error rates reflect impairments in suppressing reflexive saccades and have been associated with poor inhibition, low impulse control, agitation, excitement, and hostility (Fukumoto-Motoshita et al. 2009). Antisaccades also provide a clear distinction between schizophrenia patients and healthy controls (Zanelli et al. 2005).

In prosaccade tasks, individuals are instructed to look in the direction of the distracting stimulus. Schizophrenia patients typically perform similarly to healthy controls in this task (Smyrnis et al. 2004, Ettinger et al. 2006), suggesting that the fundamental saccade circuitry may remain intact in schizophrenia. However, some studies have shown significantly longer prosaccade latencies in schizophrenia patients compared to healthy controls (Leonard et al. 2013, Subramaniam et al. 2018). The authors of these studies hypothesize that adding secondary tasks to the prosaccade task could disrupt performance and cause delays.

In a study by Obyedkov and colleagues, patients were divided into three subgroups: predominantly negative symptoms, predominantly positive symptoms, and predominantly disorganized symptoms. Horizontal eye movements, peak velocity, latency, and accuracy were recorded for all saccade-related tasks (prosaccade, antisaccade, and predictive saccade). Additionally, error rates in antisaccade tasks were measured. Consistent with previous reports, all schizophrenia patients performed worse than healthy controls across all tasks. The findings revealed that all three patient subgroups made more antisaccade errors than healthy controls, reflecting a failure in response inhibition. Notably, patients with disorganized symptoms exhibited more errors in antisaccade tasks than the other two subgroups. Moreover, patients with negative symptoms were characterized by distinct oculomotor parameters compared to other subgroups. This finding aligns with existing literature on motor, cognitive, and neuropathological differences between patients with prominent negative symptoms and those without. Furthermore, delays were reported to correlate more closely with negative symptoms than with accuracy. Patients with positive symptoms showed prolonged latencies in both predictive and reflexive tasks, providing valuable insights into delays as potential markers of negative symptoms (Obyedkov et al. 2019).

Other studies suggest that the saccadic movements of schizophrenia patients are associated with different symptoms of the disorder. Specifically, negative symptoms and cognitive impairments are linked to greater abnormalities in saccadic performance (Winograd-Gurvich et al. 2008, Waters et al. 2009). Another study found a significant positive correlation between hallucination sub-scores and total antisaccade error rates in schizophrenia patients (Subramaniam et al. 2018). Such correlations are particularly intriguing, as psychiatric disorders are highly heterogeneous, and these specific correlations may help elucidate the neurobiological basis of psychiatric symptoms.

Interestingly, studies examining clinically unaffected relatives of schizophrenia patients frequently report increased eye-tracking dysfunction (Levy et al. 2010). Research on saccadic function has also shown significant differences between unaffected relatives and healthy controls. Among high-risk clinical participants, antisaccade task performance closely resembled that of schizophrenia patients (Luna et al. 2008).

Smooth Pursuit Eye Movement Abnormalities in Schizophrenia

Disruptions in smooth pursuit eye movements observed in schizophrenia patients indicate severe impairments in these mechanisms (Krauzlis 2004, Faiola et al. 2020). Notably, such smooth pursuit dysfunctions have also been reported in first-degree relatives of schizophrenia patients (Calkins et al. 2008).

Smooth pursuit eye movements require the coordinated movement of the eyes to continuously match the movement of a target object. In schizophrenia patients, this process is often impaired, with eye movements lagging behind the target, leading to corrective saccadic movements (Lisberger 2015). These corrective movements occur as the eyes attempt to align with the visual target, highlighting the extent of eye movement dysfunction in schizophrenia (Hutton and Ettinger 2006, Lencer et al. 2015).

Smooth pursuit abnormalities are typically caused by difficulties in matching eye movement velocity to the target's motion. This misalignment results in performance deficits in tracking (Kojima et al. 1990, Lisberger 2010). Such misalignment indicates that both motor and cognitive functions of the visual system are affected.

Predictive smooth pursuit involves anticipating the future positions of moving objects, and impairments in this type of pursuit are associated with continuous tracking deficits (Lencer et al. 2015). In schizophrenia patients, predictive smooth pursuit eye movements often fail to align with the motion of the target, which can be explained by the impact on both motor and cognitive functions (Benson et al. 2012).

Exploratory Eye Movements in Schizophrenia

In 1972, Moriya et al. first reported eye movement abnormalities in schizophrenia patients using an exploratory eye movement test (Moriya et al. 1972). Since then, numerous studies have consistently documented exploratory eye movement dysfunctions in schizophrenia (Holzman et al. 1973, Kojima et al. 1990, 1992).

Schizophrenia is a complex psychiatric disorder characterized by impairments in cognitive, emotional, and perceptual functions, and eye movements can serve as an important indicator of how these functions are disrupted (Morita et al. 2020). The examination of exploratory eye movements is considered a biological marker of schizophrenia, reflecting visual-cognitive dysfunction and attention deficits. Previous studies have shown that most schizophrenia patients exhibit abnormal eye trajectories, make fewer fixations in memory tasks, and

have a narrower range of eye movements compared to healthy controls (Ryu et al. 2001, Nakayama et al. 2003, Morita et al. 2017).

Table 2 Comparison of eye movements in schizophrenia and other disorders over the last 5 years

Study	Compared Function	Compared Disorders (Participants)	Results
Whitford et al. 2023	Sentence-level reading fluency and perceptual span	Schizophrenia (20), Dyslexia (19), Healthy Control (33)	Both schizophrenia and dyslexia groups showed similar reductions in sentence-level reading fluency compared to matched control groups. However, despite these reductions, the dyslexia group exhibited a larger perceptual span than the schizophrenia group.
Chrobak et al. 2022	Convergence eye movements in tracking moving objects	Schizophrenia (28), Bipolar Disorder (32), Healthy Control (25)	Schizophrenia patients demonstrated greater reductions in maximum convergence and divergence compared to bipolar disorder patients. Additionally, deficits in tracking accuracy with the non-dominant eye were observed.
Shiino et al. 2020	Fixation, smooth pursuit, and free-viewing tasks	Schizophrenia (83), Autism Spectrum Disorder (17), Healthy Control (255)	Individuals with autism spectrum disorder exhibited more fixations, saccades, scanning path lengths, horizontal position gains, and fewer blinking movements compared to schizophrenia patients.
St Clair et al. 2022	Fixation duration, free-viewing, and smooth pursuit tasks	Schizophrenia (120), Bipolar Disorder (141), Major Depressive Disorder (146), Healthy Control (142)	Tasks that best differentiated individuals with schizophrenia from other groups were free-viewing and fixation tasks. The schizophrenia group showed restricted scanning patterns when viewing static images and had difficulty suppressing saccadic movements in response to distractors during fixation tasks.

Ryu et al. observed that schizophrenia patients may aimlessly fixate on specific parts of an image without properly focusing their attention (Ryu et al. 2001). Similarly, Shakow reported that schizophrenia patients struggle to focus their attention on the external environment or perform meaningful orienting movements (Shakow 1962). In the context of face recognition, Williams et al. noted that under more challenging task conditions, schizophrenia patients fail to focus their gaze on key facial areas, cannot form an initial gestalt representation, and experience sequential processing abnormalities (Williams et al. 1999). These studies represent some of the earliest evidence of deviations in eye movement tasks among schizophrenia patients.

Analyzing exploratory eye movements is considered a powerful method for understanding cognitive dysfunction in schizophrenia (Kraus and Keefe 2007). Eye movements in schizophrenia patients are typically characterized by shorter scanning paths and narrower search response scores. Morita et al. reported that, compared to healthy individuals, schizophrenia patients display shorter scanning paths and focus on more restricted areas (Morita et al. 2019). This suggests difficulties in scanning and processing environmental information. Similarly, a study by Bestelmeyer et al. found that schizophrenia patients exhibit significantly different scanning paths compared to healthy controls, tending to scan visual scenes within a more confined area (Bestelmeyer et al. 2006).

Sprenger et al. provided similar findings, highlighting that schizophrenia patients are characterized by narrower scanning paths and fewer fixations (Sprenger et al. 2013). These impairments in eye movements are associated with deficits in cognitive flexibility and attentional processes. Specifically, the cognitive and attentional inflexibility observed in schizophrenia patients may manifest as impairments in exploratory eye movements (Van der Stigchel et al. 2006).

Exploratory eye movements in schizophrenia are considered critical indicators for understanding the visual projection of cognitive processes. Research in this area holds significant potential for better understanding the relationship between schizophrenia and cognitive and emotional processes. Moreover, these insights could play a crucial role in advancing treatment approaches.

Comparison of Eye Movements in Schizophrenia and Other Disorders

The comparison of cognitive and perceptual functions across various psychiatric conditions, such as schizophrenia, dyslexia, bipolar disorder, autism spectrum disorder, and major depressive disorder, provides valuable insights into the interactions between these disorders. Information summarizing studies from the past five years is presented in Table 2.

Research indicates that both individuals with schizophrenia and dyslexia experience similar difficulties with sentence-level reading fluency. However, the dyslexia group demonstrates a higher perceptual capacity compared to schizophrenia patients (Whitford et al. 2023). In the context of eye movement tracking, schizophrenia patients exhibit more pronounced limitations in convergence and divergence abilities compared to those with bipolar disorder, with noted deficiencies in accuracy when tracking with the non-dominant eye (Chrobak et al. 2022).

Studies evaluating fixation and free-viewing tasks report that individuals with autism spectrum disorder exhibit more fixations and saccades, which contrasts with the restricted visual exploration observed in schizophrenia patients (Shiino et al. 2020). Additionally, the ability to manage distractors on static images is significantly impaired in individuals with schizophrenia, who display distinctive saccadic movement profiles.

These findings highlight the complex cognitive profiles specific to each disorder and reveal distinct challenges in visual and perceptual processing across different psychiatric conditions.

Discussion

This review comprehensively examines research on eye movements in schizophrenia, detailing the effects of the disorder on smooth pursuit, saccadic movements, and exploratory eye movements. Eye movement abnormalities in schizophrenia are considered significant indicators that may represent early signs of the disease, offering valuable insights into its motor, cognitive, and neuropathological aspects.

In individuals with schizophrenia, smooth pursuit eye movements often exhibit difficulties in focusing on targets, characterized by corrective saccades (Lisberger 2015). This means their gaze frequently lags behind the target and attempts to recapture it through corrective movements. These findings highlight challenges in adapting to the velocity of visual targets and the relationship between these difficulties and motor and cognitive functions. Predictive smooth pursuit deficits in schizophrenia are linked to impairments in both cognitive and motor processes (Benson et al. 2012).

Saccadic eye movements, particularly in antisaccade and prosaccade tasks, show significant impairments in schizophrenia (Ettinger et al. 2006, Waters et al. 2012). These deficits indicate anomalies in attention and control mechanisms, directly associated with negative symptoms and cognitive impairments of schizophrenia. High error rates in antisaccade tasks reflect problems in attention and control mechanisms, while low performance in prosaccade tasks highlights dysfunctions in reflexive movement processing (Smyrnis et al. 2004, Radant et al. 2007). In this context, the relationship between saccadic eye movements and the cognitive and functional impairments in schizophrenia warrants further investigation.

Exploratory eye movements in schizophrenia are characterized by restricted scanning paths and fewer fixations (Morita et al. 2020). This reflects difficulties in scanning and processing environmental information. Impairments in exploratory eye movements are associated with deficits in cognitive flexibility and attention processes, supporting a hypothesis linking these deficits to the cognitive symptoms of schizophrenia (Ryu et al. 2001, Nakayama et al. 2003). Understanding the relationship between eye movements and cognitive functions is crucial for developing new treatment approaches.

Recent research highlights similarities and differences in cognitive and perceptual functions across psychiatric conditions such as schizophrenia, dyslexia, bipolar disorder, autism spectrum disorder, and major depressive disorder. Individuals with dyslexia experience similar challenges in sentence-level reading fluency as those with schizophrenia but exhibit a higher perceptual capacity (Whitford et al. 2023). Patients with schizophrenia show more pronounced restrictions in eye movement tracking compared to those with bipolar disorder and face challenges in handling distractors (Chrobak et al. 2022). These findings underscore the unique cognitive profiles of each disorder and reveal distinct difficulties in perceptual processing among different psychiatric conditions.

Conclusion

Eye movement abnormalities in schizophrenia should be regarded as early signs of the disorder and hold potential as valuable biomarkers for diagnosis and treatment. Future studies should investigate the effects of genetic, neurobiological, and cognitive processes on eye movements in greater detail and explore how these abnormalities can be integrated into treatment approaches for schizophrenia. Additionally, future interventions targeting eye movements could serve as significant support alongside pharmacological treatments in managing and rehabilitating schizophrenia symptoms. Developing a more comprehensive understanding of the effects of

schizophrenia on eye movements is essential for understanding the disorder's impact on cognitive and motor systems. In this context, further research on how eye movement abnormalities relate to the overall symptomatology and treatment strategies for schizophrenia will provide important theoretical and practical contributions.

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