ISTRAŽIVANJA DISLEKSIJE METODOM MJERENJA POKRETA OKA

USE OF THE EYE-TRACKING METHOD IN RESEARCH ON DYSLEXIA

MARIJAN PALMOVIĆ

University of Zagreb, Faculty of Education and Rehabilitation Sciences, Borongajska cesta 83 f, Zagreb, Croatia, contact: marijan.palmovic@erf.unizg.hr

Received: 03.03.2025.
Accepted: 31.03.2025.

Review paper
UDK: 616.89-008.434.5:004
https://doi.org/10.31299/hrri.61.1.9

Sažetak: *Razvojem neinvazivnih uređaja jednostavnih za upotrebu mjerenje pokreta oka postaje sve zastupljenija u istraživanjima jezične obrade. U radu se prikazuje upotreba uređaja za mjerenje pokreta oka u istraživanjima disleksije, i to u svim vidovima proučavanja tog poremećaja, od etiologije do dijagnostike i terapije. U istraživanjima koja se bave uzrocima disleksije suprotstavljena su dva stajališta: „lingvističko“ i „nelingvističko“ s obzirom na to vide li se uzroci u fonološkim problemima ili su oni posljedica deficita na drugim kognitivnim ili biološkim funkcijama (npr. okulomotorni deficit). U trijaži i dijagnostici metoda mjerenja pokreta oka sve se više oslanja na algoritme strojnog učenja koji signal s uređaja automatski klasificiraju. Razvoj fontova i aplikacija najčešći je način upotrebe metode mjerenja pokreta oka u terapiji.*

Ključne riječi: *mjerenje pokreta oka, disleksija, čitanje, etiologija, dijagnostika, asistivne tehnologije, pregled literature*

Abstract: *With the development of non-invasive and easy-to-use devices, the measurement of eye movement is becoming increasingly common in research on language processing. This paper presents the use of eye-tracking devices in dyslexia research, encompassing all aspects of research on this disorder, from aetiology to diagnosis and therapy. In studies examining the causes of dyslexia, two opposing perspectives are presented: the "linguistic" and "non-linguistic" viewpoints, depending on whether the causes are attributed to phonological problems or considered a consequence of deficits in other cognitive or biological functions (e.g., oculomotor deficits). In screening and diagnosis, methods used to measure eye movement increasingly rely on machine learning algorithms that automatically classify signals from the device. The development of fonts and applications is the most common way of incorporating eye movement measurement in therapy.*

Keywords: *eye-tracking, dyslexia, reading, aetiology, diagnostics, assistive technology, literature review*

UVOD

Disleksija se klasificira kao specifični poremećaj učenja koji definiraju problemi u točnosti i tečnosti u prepoznavanju riječi te u otežanom dekodiranju i problemima u pravopisu (DSM–5; *American Psychiatric Association*, 2013). Čitanje kod osoba s disleksijom karakterizira slaba točnost, smanjena brzina čitanja i problemi s razumijevanjem pročitanog. Disleksija pogađa 5-10 % populacije (prema *International Dyslexia Association*, https://dyslexiaida.org/) i značajno utječe na akademski uspjeh djece koja su njome pogođena. Uz to, iako po logici stvari nasljedni čimbenik igra jed-

INTRODUCTION

Dyslexia is classified as a specific learning disorder characterised by difficulties in word recognition accuracy and fluency, as well as impaired decoding and spelling problems (DSM-5; American Psychiatric Association, 2013). Individuals with dyslexia typically exhibit poor reading accuracy, reduced reading speed, and difficulties in reading comprehension. Dyslexia affects 5-10% of the population (according to the International Dyslexia Association, https://dyslexiaida.org/) and it significantly impacts the academic success of affected children.

naku ulogu i u alfabetskim i u nealfabetskim jezicima, razlike u jezicima i, posebno, pismima, kao i u ortografijama (tj. u načinu na koji se u pismu preslikavaju glasovi u slova) utječu na specifične osobine disleksije u pojedinom jeziku, pa se može govoriti o okolinskim ili kulturnim čimbenicima. Tako je isprepletenost mnogih čimbenika uz sličnosti u bihevioralnim simptomima s drugim poremećajima (npr. ADHD) još uvijek izazov za istraživanje disleksije; Uta Firth tako govori o „paradoksima“ u definiranju disleksije (Firth, 1999) shvaćajući je kao sindrom koji se ne može objasniti samo na jednoj od razina analize, biološkoj, kognitivnoj, bihevioralnoj ili okolinskoj[1].

Budući da nema bioloških markera pomoću kojih bi se jednostavno dijagnosticirala disleksija, metode koje se upotrebljavaju u kognitivnoj neuroznanosti ne mogu se upotrijebiti za dijagnosticiranje disleksije. U novije se vrijeme stoga istraživanja disleksije okreću metodi mjerenja pokreta oka kao metodi koja mjeri automatske procese jezične obrade na bihevioralnoj i fiziološkoj razini. Ta se istraživanja temelje na pretpostavci “oko - um”, tj. na pretpostavci da se oko automatski usmjerava na ono na što osoba u tom trenutku usmjerava pažnju, tj. na ono što u tom trenutku njegov um obrađuje (Just i Carpenter, 1976). Metoda mjerenja pokreta oka stoga neposredno daje podatke o vizualnoj obradi, a posredno o kognitivnoj, tj. jezičnoj obradi. Budući da su obje uključene u čitanje, metoda mjerenja pokreta oka čini se idealnom za proučavanje disleksije.

U takvim se istraživanjima najčešće upotrebljavaju uređaji za mjerenje pokreta oka koji otkrivaju sredinu zjenice i kornealni refleks svjetla u bliskom infracrvenom području pa orijentaciju oka izračunavaju kao vektor između tih dviju točaka. Nadalje, za istraživanja čitanja upotrebljavaju se uređaji s velikom brzinom uzorkovanja, danas najčešće od 1 ili čak 2 kHz tako da se položaj oka može izračunati iz milisekunde u milisekundu (za 1 kHz). Ti se podaci grupiraju u tzv.

[1] Pri čemu bi biološku razinu činili genetski i neuro-anatomski čimbenici, bihevioralnu opaženo ponašanje (sporost, pogreške itd.), okolinsku poduka i socio-ekonomski čimbenici, dok bi kognitivnu razinu predstavljali mehanizmi obrade informacija, među kojima su najvažniji mehanizmi jezične obrade.

Moreover, although hereditary factors logically play an equal role in both alphabetic and non-alphabetic languages, linguistic differences - particularly in writing systems and orthographies (i.e., the way sounds are mapped to letters in writing) – can influence the specific characteristics of dyslexia in each language. This suggests that environmental or cultural factors also play a role.

The interplay of multiple factors, along with behavioural similarities between dyslexia and other disorders (e.g., ADHD), continues to pose a challenge for dyslexia research. Uta Frith, for example, refers to “paradoxes” in defining dyslexia (Frith, 1999), viewing it as a syndrome that cannot be explained solely at one level of analysis - whether biological, cognitive, behavioural, or environmental.[1]

Since there are no biological markers that can be used to diagnosis dyslexia easily, methods used in cognitive neuroscience cannot be applied for its diagnosis. Recently, dyslexia research has increasingly turned to eye-tracking as a method that measures automatic language processing at both behavioural and physiological levels.

These studies are based on the “eye-mind” hypothesis, which assumes that the eye automatically focuses on whatever the person is paying attention to at a given moment (i.e.,) whatever their mind is processing at that time (Just & Carpenter, 1976). Eye-tracking, thus, provides direct data on visual processing and indirect data on cognitive, i.e., linguistic processing. Since both processes are involved in reading, eye-tracking appears to be an ideal method for studying dyslexia.

In such studies, eye-tracking devices are commonly used to detect the centre of the pupil and the corneal reflection of infrared light, calculating eye orientation as a vector between these two points. Furthermore, research on reading utilises

[1] The biological level includes genetic and neuroanatomical factors, the behavioural level refers to observed behaviour (such as slowness, errors, and so on), the environmental level encompasses instruction and socio-economic factors, while the cognitive level represents information processing mechanisms, with language processing mechanisms being the most important.

događaje (engl. *events*) koji su u istraživanjima čitanja sakade i fiksacije. Sakade su brzi pokreti oka u jednom smjeru (čak i 700°/s) i traju kratko, kod čitanja najčešće 20-30 ms. Njihov domet mjerimo amplitudom u stupnjevima vizualnog kuta (tj. kut koji čini točka početka i točka kraja sakade) i njezinom brzinom. Fiksacije su razdoblja između sakada. Za vrijeme fiksacije oko je relativno mirno i sudionik je fokusiran na ono što je u fovealnom vidu. Kod čitanja fiksacije tipično traju od 100 do 400 ms. Čitanje je tako smjena fiksacija i sakada, iako se čitatelju čini kao da mu oko klizi po tekstu. Upravo zato što je ta smjena fiksacija i sakada nesvjesna, njihovo mjerenje pruža uvid u automatske jezične ili kognitivne procese koji se odvijaju u pozadini jezične obrade.

Jezična, tj. psiholingvistička istraživanja metodom mjerenja pokreta oka dolaze u više okusa od kojih se mogu izdvojiti dva najčešća: tzv. paradigma vizualnog svijeta (engl. *visual world paradigm*) i paradigma čitanja (engl. *reading paradigm*). U prvoj se jezični podražaj, a to su, tipično, rečenice, prikazuje slušno, dok se na zaslonu računala prikazuje slika. Ta se slika najčešće sastoji od prizora koji se odnosi na rečenicu, ali ona može biti sastavljena i od više slika koje se odnose na pojedine riječi u rečenici ili dijelove rečenice. U takvim se eksperimentima mjeri u kojem je trenutku u rečenici sudionik pažnju usmjerio na neki predmet na slici ili na neku od ponuđenih slika. To može biti i prije nego što se odgovarajuća riječ pojavi u slušalicama sudionika; tada se govori o anticipirajućim pokretima oka i oni su dobra mjera izgradnje sintaktičke strukture rečenice. Osim članaka u kojima se razni zadaci kombiniraju, paradigma vizualnog svijeta najčešće se u istraživanjima disleksije pojavljuje kao paradigma vizualne pretrage (engl. *visual search paradigm*), kao u npr. Kutlu i sur. 2024. Paradigma čitanja u kojoj sudionik jednostavno sjedi pred zaslonom računala i čita rečenice ili odlomke teksta dok mu se mjere pokreti oka ostaje najprirodnija metoda istraživanja disleksije metodom mjerenja pokreta oka.

Metoda mjerenja pokreta oka danas se upotrebljava u svim vidovima istraživanja disleksije. Zato će se za pregled istraživanja disleksije

high-sampling-rate devices, typically at 1 or even 2 kHz today, allowing eye position to be calculated millisecond by millisecond (at 1 kHz).

These data are grouped into so-called events, which correspond to saccades and fixations in reading research. Saccades are rapid eye movements in one direction (up to 700°/s) that are brief, typically lasting 20-30 ms during reading. Their range is measured by amplitude in degrees of visual angle (the angle between the start and end points of the saccade), as well as by speed. Fixations are the periods between saccades when the eye is relatively still and the participant focuses on what is in their foveal vision. During reading, fixations typically last between 100 and 400 ms. Reading, therefore, consists of alternating fixations and saccades, even though it may seem to the reader as if his eyes glide smoothly across the text.

Because this alternation between fixations and saccades occurs subconsciously, measuring them provides insights into automatic linguistic or cognitive processes occurring in the background of language processing.

Linguistic or psycholinguistic research using the eye-tracking method comes in several forms, with two of the most common being the visual world paradigm and the reading paradigm. In the first, the linguistic stimulus - typically sentences - is presented auditorily, while an image is displayed on a computer screen. This image often represents a scene related to the sentence, though it can also consist of multiple images corresponding to individual words or parts of the sentence.

In these experiments, researchers measure the moment within the sentence when the participant directs their attention to an object in the image or one of the offered images. This can even occur before the corresponding word is heard through the participant's headphones, in which case, it is referred to as anticipatory eye movements, which is a useful measure of sentence structure construction. Aside from studies that combine different tasks, the visual world paradigm most commonly appears in dyslexia research in the form of the visual search paradigm (e.g., Kutlu et al., 2024).

upotrijebiti jednostavna i pedagoški logična klasifikacija znanja o bilo kojem poremećaju, klasifikacija kakvu se obično može naći u medicinskim priručnicima (npr. *Merck Manuals*, https://www.msdmanuals.com/home ili Kasper i sur. 2005). Disleksija će se u ovome pregledu promatrati kroz istraživanja etiologije i patologije, simptomatologije i dijagnostike te tretmana tj. terapije. Metoda praćenja pokreta oka našla je svoju primjenu u istraživanjima svakog od spomenutih elemenata znanja o disleksiji, tako da se danas već može govoriti o cjelovitoj slici koju metoda mjerenja pokreta oka pruža o disleksiji.

METODOLOGIJA

Za ovaj sustavni pregled literature upotrijebljeni su relevantni elementi protokola PRISMA za sustavan pregled literature (Page i sur., 2021). To uključuje jasnu identifikaciju glavnih ciljeva ili pitanja, kriterija uključivanja ili isključivanja pojedinih studija i navođenje baza podataka na kojima se obavila pretraga. Također, potrebno je prepoznati rizik od moguće pristranosti (engl. *bias*) i navesti metode upotrijebljene za dobivanje rezultata. Naravno, potrebno je sažeti glavne karakteristike i rezultate studija te dati njihovo tumačenje. Konačno, katkada je potrebno navesti izvore financiranja studija, što se radi zbog mogućeg sukoba interesa, koji je u logopedskim istraživanjima ipak rijedak. Dijagram postupka nalazi se na Slici 1.

The reading paradigm, in which a participant simply sits in front of a computer screen and reads sentences or text passages, while their eye movements are measured, remains the most natural method for studying dyslexia through eye-tracking.

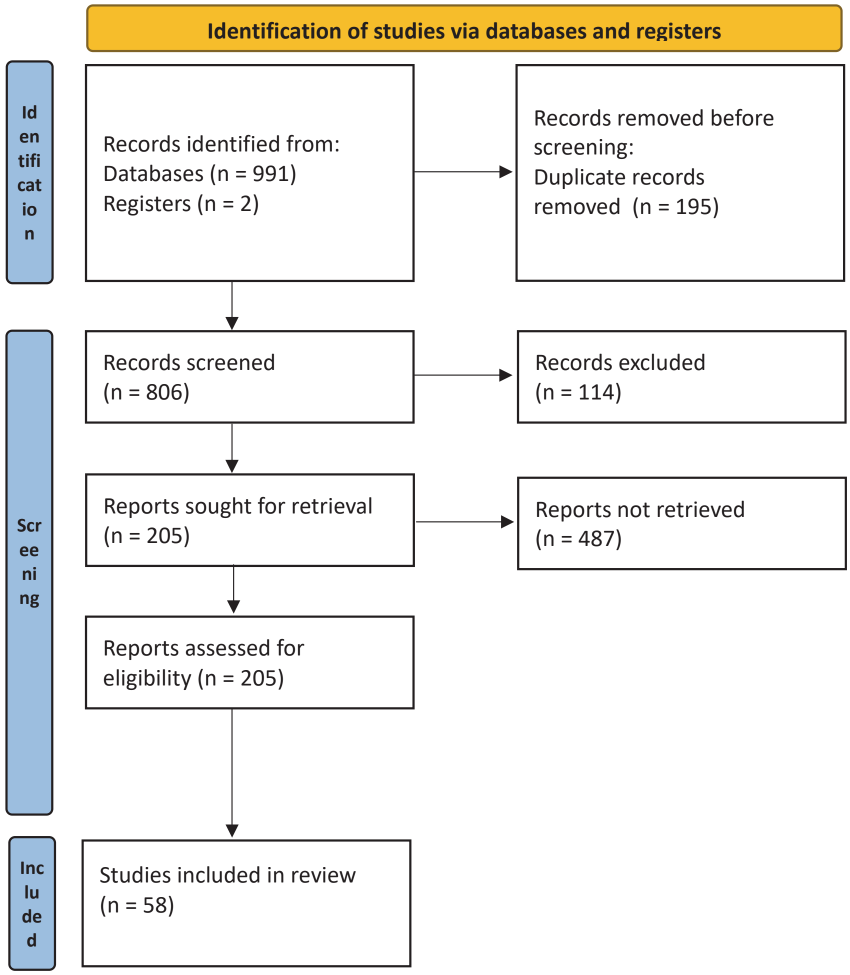
Today, the eye-tracking method is used in all areas of dyslexia research. Therefore, this review of dyslexia research with eye-tracking will follow a simple and pedagogically logical classification of knowledge about any disorder - the type of classification typically found in medical manuals (e.g., *Merck Manuals* - https://www.msdmanuals.com/home, or Kasper et al., 2005). Dyslexia will be examined through research on aetiology and pathology, symptomatology and diagnosis, and treatment or therapy.

The eye-tracking method has been applied in studies of each of these aspects of dyslexia, allowing researchers to present a comprehensive picture that eye-tracking provides in understanding dyslexia.

METHODOLOGY

Relevant elements of the PRISMA protocol for systematic reviews (Page et al., 2021) were incorporated into this systematic literature review. This includes a clear identification of the main objectives or research questions, inclusion and exclusion criteria, and a specification of the databases used for the search. Additionally, it is necessary to recognise the risk of potential bias and outline the methods used for obtaining results. Naturally, the main characteristics and findings of the studies were summarised and interpreted. Finally, in some cases, sources of funding needed to be disclosed to address potential conflicts of interest, although such conflicts are rare in speech-language pathology research. Figure 1 depicts the study selection process.

Slika 1. *Dijagram postupka odabira članaka /* ***Figure 1.*** *Flowchart depicting the study selection procedure*



Budući da se metoda mjerenja pokreta oka u istraživanjima disleksije upotrebljava i u temeljnim istraživanjima etiologije i patologije, tj. same prirode disleksije, u prepoznavanju simptoma i dijagnostici kao i u terapiji, cilj je procijeniti gdje je metoda mjerenja pokreta oka najbolja, u kojem se vidu istraživanja disleksije ona najviše upotrebljava i gdje ona daje novi uvid u tu teškoću. Kvantificirani podaci o istraživanjima pojedinog vida disleksije mogu otkriti i eventualnu pristranost u istraživanjima, kako je to uobičajeno. Također, cilj je pokazati u kojem se smjeru kreće razvoj metode mjerenja pokreta oka u istraživanjima disleksije.

Since eye-tracking is used in dyslexia research across different areas - fundamental research on aetiology and pathology (i.e., the nature of dyslexia itself), symptom recognition and diagnosis, and treatment - the aim is to assess where eye-tracking is most effective, in which areas of dyslexia research it is most frequently applied, and where it provides new insights into the disorder. Quantified data on research in specific aspects of dyslexia may also reveal potential biases in studies, as is common in systematic reviews. Additionally, this review aims to highlight the direction of development of eye-tracking methodology in dyslexia research.

REZULTATI

Za potrebe ove studije pregledani su radovi u dvjema bazama podataka, *Web of Science* i *Scopus*. Pretraga je sadržavala dva pojma "*dyslexia*" i "*eye-tracking*", tj. "*eyetracking*" kao varijantu i dala je ukupno 991 rad, s tim da se 195 radova nalazilo u objema bazama; drugim riječima, pretražene su baze sadržavale 796 jedinstvenih radova. Analiza referenci nađenih u *Web of Science* prikazuje rezultate po područjima (Slika 1).

RESULTS

For the purpose of this study, papers were reviewed from two databases - Web of Science (WoS) and Scopus. The search included two terms - "dyslexia" and "eye-tracking" (or "eyetracking" as a variant), yielding a total of 991 papers, with 195 papers appearing in both databases. In other words, the databases contained 796 unique papers. An analysis of the references found in Web of Science categorised the results by research area (Fig. 2).

Slika 2. *Rezultati pretrage* Web of Science *prema područjima radova (prema klasifikaciji WoS) /* ***Figure 2.*** *Web of Science search results categorised by research area (according to WoS classification).*

Ta analiza pokazuje da ukupno 56 % istraživanja disleksije metodom mjerenja pokreta oka u novije vrijeme pripada području psihologije. U novije je vrijeme izrazito porastao broj istraživanja koja pripadaju računalnoj znanosti, tj. koja se bave automatskom obradom podataka prikupljenih metodom mjerenja pokreta oka kod sudionika s disleksijom.

Jezikoslovlje (tj. psiholingvistička istraživanja) kao i logopedska istraživanja disleksije ovom metodom slabo su zastupljena (jezikoslovlje: 10 %, logopedija, kad se uz pedagogiju, klasificira kao obrazovna znanost, tek 5 %; zbog engleskog pojma *'speech and language pathology*' logoped-

This analysis shows that, in recent years, 56% of dyslexia research using the eye-tracking method falls within the field of psychology. There has been a significant increase in studies within computer science, particularly those focusing on the automatic processing of eye-tracking data collected from participants with dyslexia.

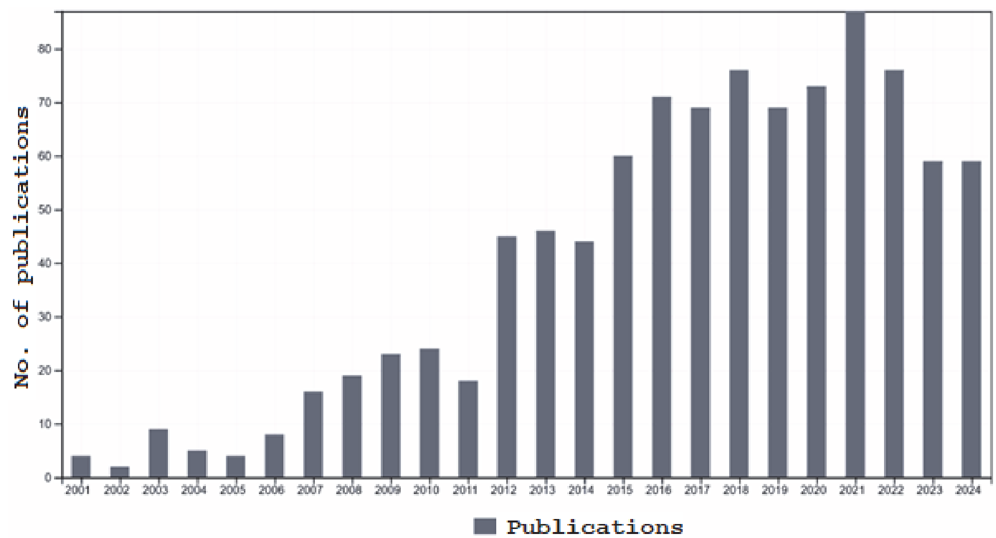
Linguistics (i.e., psycholinguistic research) and speech-language pathology studies on dyslexia using this method remain underrepresented: linguistics accounts for only 10%, while speech-language pathology, when classified under educational sciences along with pedagogy, represents just 5%. Due to the use of the English ska se istraživanja katkada klasificiraju i kao lingvistička).

Kada se promatra razvoj upotrebe metode mjerenja pokreta oka u istraživanjima disleksije, vidi se velik porast istraživanja u ovome tisućljeću (Slika 3).

term '*speech and language pathology*', some speech-language pathology studies are occasionally classified as linguistics.

When examining the growth of eye-tracking research in dyslexia, a significant increase in studies can be observed in this millennium (Fig. 3).

Slika 3. *Broj objavljenih članaka o disleksiji istraživanoj metodom mjerenja pokreta oka od 2001 /* ***Figure 3.*** *Number of published articles on dyslexia research using the eye-tracking method since 2001.*



Posljednjih godina godišnje se objavi sedamdesetak članaka (barem u časopisima citiranima u WoS-u) koji se bave proučavanjem disleksije pomoću metode mjerenja pokreta oka; čini se da je 2021. bila najplodnija s 90 članaka na tu temu. U dvadesetak godina 21. stoljeća to je velik porast s obzirom na to da se ta metoda rijetko pojavljivala u istraživanjima disleksije krajem prošlog i početkom ovoga stoljeća. Porast je djelomično rezultat napretka u samoj tehnici mjerenja pokreta oka, tj. u sve većem broju sve dostupnijih uređaja jednostavnih za upotrebu. Također, taj je porast bar dijelom usputna posljedica općeg porasta broja objavljenih znanstvenih članaka, pa bi bilo pogrešno izvoditi bilo kakve zaključke samo na temelju porasta broja objavljenih istraživanja. Isto tako, pad koji se uočava u 2022-2023. posljedica je činjenice da su mnogi laboratoriji bili zatvoreni za vrijeme pandemije; ona je bila velika prepreka u istraživanjima u kojima sudionik mora fizički doći u laboratorij i tamo u zatvorenom proboraviti

In recent years, around 70 articles per year (at least in journals indexed in Web of Science) have been published on dyslexia research using eye-tracking methods. The most productive year appears to have been 2021, with 90 articles on the topic. This represents a significant increase over the past two decades, considering that eye-tracking was rarely used in dyslexia research at the end of the last century and in the early 2000s. This growth is partly due to advancements in eye-tracking technology, making devices more accessible and easier to use. However, the increase in the number of publications is also influenced by an overall rise in the number of scientific articles published, meaning that conclusions should not be drawn based solely on publication trends. The decline observed in 2022-2023 can be attributed to pandemic-related laboratory closures, as eye-tracking experiments require participants to be physically present in a controlled environment for extended periods of time. While online sat-dva. *Online* rješenja preko internetske kamere i pretraživača, iako sve naprednija, još nisu dovoljno precizna za mjerenje pokreta oka kod čitanja. Ipak, trend porasta broja članaka postojan je i slični se podaci, kako su prikazani na Slici 1 i 2 mogu dobiti i za članke objavljene u časopisima citiranima u *Scopusu*.

Bibliografski podaci iz obje su baze izvezeni u .ris formatu i učitani u program za obradu bibliografskih jedinica *Rayyan* (https://www.rayyan.ai/) koji omogućava otkrivanje duplikata (tj. članaka citiranih u objema bazama) i postavljanje vlastitih kriterija uključivanja i isključivanja. Tako su isključeni pregledni članci i meta-analize te poglavlja u knjigama, a uključeni su samo članci koji sadrže izvorna znanstvena istraživanja. Također, dodane su vlastite ključne riječi kako bi se lakše klasificirali uključeni članci. Nakon konačnog odabira članaka pristupilo se njihovoj obradi kako bi se za svaki od njih utvrdio cilj istraživanja, uzorak (sudionici, jezik, pismo), kakvi su bili podražaji, tj. kakav je bio zadatak, što se mjerilo (tj. koje mjere koje omogućuje uređaj), koji su bili rezultati i, eventualno, ograničenja istraživanja. Za taj je korak bilo potrebno pregledati same radove (ne samo sažetke). Radovi su zatim klasificirani u tri kategorije s obzirom na to kojim se vidom disleksije bave. Tako su moguće generalizacije o uzrocima ili prirodi disleksije, njezinim simptomima i dijagnostici te o mogućim tretmanima. Budući da je ukupan broj radova velik, za detaljniji se prikaz uzimaju najvažniji (u smislu predstavljanja neke skupine sličnih istraživanja) ili, pak, oni radovi koji donose neku novost u istraživanjima, kako je to uobičajeno. Tako je omogućen detaljniji prikaz pojedinih radova, što možda daje bolji uvid u način na koji se mjerenje pokreta oka upotrebljava u proučavanju disleksije od samog nabrajanja brojnih radova.

Etiologija

Otprilike 40% svih studija uzetih u razmatranje u ovome pregledu istražuje uzroke disleksija mjerenjem pokreta oka (filtrira li se cijela bibliografija odgovarajućim dodanim ključnim riječima, ostaje 84 članaka, ali u svakome od njih nije fokus na istraživanju uzroka disleksije, nego često

eye-tracking solutions using webcams and browsers are becoming more advanced, they lack the precision needed for reading-related eye movement research. Nevertheless, the upward trend in publications remains consistent, and similar patterns (as shown in Fig. 2 and 3) can be observed in Scopus-indexed journals.

Bibliographic data from both Web of Science and Scopus were exported in the .ris format and processed using Rayyan (https://www.rayyan.ai/), which facilitated the detection of duplicates and allowed for custom inclusion and exclusion criteria. Review articles, meta-analyses, and book chapters were excluded; only original research studies were included. Additional keywords were assigned to aid in the classification process. After the final selection of articles, each study was analysed based on research objectives, sample (participants, language, writing system), stimuli and tasks, eye-tracking measures used, as well as results and limitations. The studies were then classified into three categories based on their focus: causes/nature of dyslexia (aetiology and pathology), symptoms and diagnosis, and treatment and interventions. Considering the large number of existing studies, the most relevant studies were selected for detailed analysis, including those that represent a broader group of similar studies or those that introduce novel insights into dyslexia research. It is expected that this approach can provide a more in-depth understanding of how eye-tracking contributes to dyslexia research, rather than simply listing numerous studies.

Aetiology

Approximately 40% of all journal articles analysed here investigated the causes of dyslexia by measuring eye movements. When the entire bibliography is filtered with appropriate additional keywords, 84 articles remain. However, not all of them focus on investigating the causes of dyslexia; many aim to confirm a narrowly formulated hypothesis within a particular theory of dyslexia or a hypothesis related to a specific language or orthography. For example, Huang et al. (2008) examined the "visuospatial cognitive deficit" as a potential cause of dyslexia, but this deficit is disna traženju potvrde za uže formuliranu hipotezu unutar neke od teorija disleksije ili hipotezu koja se odnosi na pojedini jezik ili ortografiju, kao što je to npr. Huang i sur, 2008 u kojem se, doduše, problematizira „vizuospacijalni kognitivni deficit" kao uzrok disleksije, ali se taj deficit stavlja u kontekst čitanja kineskog, ideografskoga pisma, i to u zadatku vizualne pretrage, dok se zaključci studije odnose na dobro poznatu „pojavnu", tj. bihevioralnu razinu disleksije: sporije, tj. dulje fiksacije, manje i češće sakade u djece s disleksijom, što se u tom radu tumači slabijim sposobnostima i strategijama obrade vizualnih obavijesti i u nejezičnim zadacima). Općenito, istraživanja uzroka disleksije mjerenjem pokreta oka mogu se razvrstati u dvije kategorije: prva, koja uzrok disleksije vidi u fonološkom deficitu, tj. deficitu fonološke svjesnosti, a što se svodi na manjak u slušnoj obradi[2] (cf. Bradley i Bryant, 1978) i druga, koja disleksiju nastoji objasniti ne-jezičnim procesima. Prva se kategorija katkada naziva i „lingvističkom" zato što se uz fonološke često nalaze i druge teškoće u jezičnoj obradi, teškoće koje se uočavaju i prije nego što se dijete uključi u poduku u čitanju (cf. Lohvansuu i sur., 2021, opsežnu longitudinalnu finsku studiju koja se ne koristi metodom mjerenja pokreta oka, ali predstavlja sveobuhvatno istraživanje disleksije i njezinih prekursora provedenu na gotovo 10000 finske djece). Radi li se o „fonološkoj teoriji" disleksije ili tek o „fonološkoj hipotezi", i danas se raspravlja (Zoccolotti, 2022). Središnju tvrdnju te teorije čini stav da se temeljni nedostatak, koji uzrokuje teškoće u čitanju, sastoji od degradiranih ili slabo specificiranih fonoloških reprezentacija (v. bilješku 2), što prethodi teškoćama s kojima se dijete susreće kad uči čitati. Same fonološke reprezentacije, kako primjećuju Ramus i Ahissar (2012), nisu neposredno dostupne istraživanju, nego se o njima zaključuje na temelju rezultata na fonološkim zadacima.

Drugoj bi kategoriji pripadale studije koje uzroke disleksije vide u senzomotoričkoj disfunk-

[2] Pozadinu manjka u slušnoj obradi neki vide u slaboj specifikaciji reprezentacija fonema (Swan i Goswami, 1997), dok drugi taj manjak objašnjavaju problemom u pristupu tim reprezentacijama (Ramus, 2014).

cussed in the context of reading Chinese, an ideographic script, within a visual search task. The study's conclusions pertain to the well-known "surface" (i.e., behavioural) manifestations of dyslexia, such as slower and longer fixations, as well as smaller, more frequent saccades in children with dyslexia, which the authors interpret as weaker abilities and strategies for processing visual information, even in non-linguistic tasks.

In general, research on the causes of dyslexia using eye movement measurements can be categorised into two groups. The first group attributes dyslexia to a phonological deficit, specifically a deficit in phonological awareness, which is ultimately a deficiency in auditory processing[2] (cf. Bradley & Bryant, 1978). The second group attempts to explain dyslexia through non-linguistic processes. The first category is sometimes referred to as the "linguistic" perspective, as phonological difficulties are often accompanied by other language-processing difficulties that can be observed even before a child's inclusion into the reading instruction (cf. Lohvansuu et al., 2021, a comprehensive longitudinal Finnish study that does not use eye-tracking, but provides an extensive investigation of dyslexia and its precursors, involving nearly 10,000 Finnish children). The debate on whether "phonological theory" or merely a "phonological hypothesis" best describes this perspective is still ongoing (Zoccolotti, 2022). The central claim of this theory is that the fundamental deficit causing reading difficulties lies in degraded or poorly specified phonological representations (see note 2), which precedes the difficulties a child encounters when learning to read. As noted by Ramus and Ahissar (2012), phonological representations themselves are not directly accessible to research, but are inferred based on performance in phonological tasks.

The second category includes studies that consider the causes of dyslexia as sensorimotor dysfunction, which also explains the frequently observed motor deficits in children with dyslexia

[2] The background of the deficiency in auditory processing is seen by some as stemming from weak specification of phoneme representations (Swan & Goswami, 1997), while others explain this deficiency as a problem in accessing these representations (Ramus, 2014).

ciji koja objašnjava i često uočene motoričke deficite u djece s disleksijom (Ramus i sur. 2003), u problemima vizualne obrade, što se često veže uz magnocelularnu teoriju disleksije (v. Stein, 2001) i u problemima pažnje kod kojih slova u parafovealnom vidu interferiraju s riječju koja se trenutačno fiksira (Rayner i sur. 2007).

Studije koje potvrđuju fonološki deficit kao uzrok disleksije upotrebljavaju obje glavne istraživačke paradigme u mjerenju pokreta oka, paradigmu vizualnog svijeta (tj. preciznije, vizualne pretrage) i, u daleko manjoj mjeri, paradigmu čitanja. Za paradigmu vizualnog svijeta pretpostavlja se da su pokreti oka povezani s leksičkom obradom tako što vrijeme fiksacije ciljne slike odražava leksičku aktivaciju (Tanenhaus et al. 2000). U dokazivanju fonološke naravi disleksije ta se pretpostavka operacionalizirala mjerenjem vremena fiksacija na ciljnu sliku u uvjetima kad su prisutni fonološki nepovezani distraktori i u uvjetima prisutnih distraktora s istim početnim ili završnim segmentima u zadatku vizualne pretrage (Desroches i sur. 2006).

Na primjer, uz ciljnu riječ *candle*, nepovezani bi distraktor bio *flower*, tj. slika cvijeta, dok bi fonološki povezani distraktori bili *candy* (početni segment) i *sandal* (rima). Duljine fiksacije u pravilu su produžene ako su prisutni fonološki povezani distraktori. U navedenoj studiji u populaciji djece s disleksijom rezultati su pokazali odsutnost statistički značajne razlike u duljini fiksacija samo u uvjetu rime (identičnog završnog segmenta riječi). Autori su to protumačili slabijom osjetljivošću djece s disleksijom na odnose „višega reda“ među riječima, tj. zaključili su da se u kategorizaciji podražaja djeca s disleksijom oslanjaju na segmentalna, a ne i na suprasegmentalna obilježja.

Na sličan se način istraživanje Araújo i sur. (2020) koristi dobro poznatim zadatkom RAN (engl. *Rapid Automated Naming*) kojim se mjeri automatiziranost kojom se poznati vizualni podražaji „prebacuju“ u jezični kôd činom imenovanja. Taj se zadatak inače pokazao dobrim prediktorom čitanja i disleksije, i to u raznim stupnjevima jezičnoga razvoja i u brojnim jezicima (za meta-analizu v. Araújo i Faísca, 2019). Metoda mjerenja pokreta oka omogućila je autorima da istraže po-

(Ramus et al., 2003), as well as problems in visual processing, often associated with the magnocellular theory of dyslexia (see Stein, 2001), and attention-related difficulties, where letters in the parafoveal vision interfere with the currently fixated word (Rayner et al., 2007).

Studies confirming phonological deficits as the cause of dyslexia employ both major research paradigms in eye movement measurement: the visual world paradigm (more precisely, visual search) and, to a much lesser extent, the reading paradigm. The visual world paradigm assumes that eye movements are linked to lexical processing, where fixation time on a target image reflects lexical activation (Tanenhaus et al., 2000). To demonstrate the phonological nature of dyslexia, this assumption has been operationalised by measuring fixation times on the target image under conditions with phonologically unrelated distractors and those with distractors sharing the same initial or final segments in a visual search task (Desroches et al., 2006).

For example, given the target word ‘*candle’*, an unrelated distractor would be ‘*flower’*, while the phonologically related distractors would be ‘*candy’* (same initial segment) and ‘*sandal’* (rhyme). Fixation durations are generally longer when phonologically related distractors are present. In the cited study (Desroches et al., 2006), results in children with dyslexia showed no statistically significant differences in fixation duration in the rhyme condition (identical final segment of the word). The authors interpreted this as weaker sensitivity in children with dyslexia to higher-order relationships between words, concluding that they rely more on segmental than suprasegmental features when categorising stimuli.

Similarly, Araújo et al. (2020) used the well-known Rapid Automatised Naming (RAN) task, which measures how efficiently familiar visual stimuli are converted into linguistic code through naming. This task has been shown to be a good predictor of reading ability and dyslexia across different stages of language development and in various languages (for a meta-analysis, see Araújo & Faísca, 2019). The eye-tracking method allowed the researchers to examine the relationvezanost leksičkog pristupa i planiranja verbalnog odgovora i kako se ta povezanost razlikuje kod odraslih osoba s disleksijom.

Duljina pogleda (engl. *gaze duration*) povezuje se s procesom prepoznavanja objekta na slici uključujući aktivaciju fonoloških kodova. Dodatno, izvedba na zadatku imenovanja mjerila se pomoću raspona oko-glas (engl. *eye-voice span, EVS*), mjere koja se odnosi na vremensku udaljenost od početka[3] pogleda na ciljnu sliku do početka verbalnog odgovora (Gordon i Hoedemaker, 2016). Budući da je EVS oko 250 ms dulji od duljine pogleda, smatra se da uključuje i kasne procese vezane za artikulaciju govora.

Araújo i Faísca (2020) manipulirali su čestotnošću i gustoćom susjedstva ciljnih riječi te dobili statistički značajne interakcije skupine (disleksija i kontrola) i čestotnosti te skupine i gustoće susjedstva. Također, interakcija između čestotnosti i gustoće susjedstva upućuje da gustoća susjedstva ima facilitirajući učinak samo za riječi niske čestotnosti, i to jednako i u skupini osoba s disleksijom i u kontrolnoj skupini. Osobe s disleksijom jednostavno su na odabranim mjerama sporije od kontrolne skupine. Autori takve rezultate tumače suboptimalnim preslikavanjem fonoloških reprezentacija u artikulacijske naredbe (potrebne za zadatak imenovanja) kod disleksije. Budući da kod osoba s disleksijom nije nađen problem na razini leksičkog pristupa (na što bi upućivale razlike između duljine pogleda i EVS u odnosu na kontrolu, autori dobivene rezultate smatraju potvrdom teorije fonološkog deficita.

Sporije anticipirajuće pokrete očiju kod osoba s disleksijom dobili su u svojoj studiji Huettig i Brouwer (2015). Ciljna slika mogla se predvidjeti iz roda člana u nizozemskom (‘*het*’ ili ‘*de*’). Kašnjenje anticipirajućih pokreta oka kod osoba s disleksijom autori shvaćaju kao potvrdu tvrdnje da je pismenost, shvaćena kao vještina čitanja i pisanja općenito (engl. *literacy*), povezana s predviđa-

[3] Autori su ustvari EVS mjerili od kraja posljednje fiksacije do početka verbalnog odgovora, što su nazvali *temporal offset-EVS*). Inače je uobičajeno mjeriti EVS od početka pogleda u odgovarajuće područje interesa do početka verbalnog odgovora.

ship between lexical access and verbal response planning, as well as understand how this differs in adults with dyslexia.

Gaze duration is associated with the process of object recognition in an image, including phonological code activation. Additionally, naming performance was measured using the eye-voice span (EVS), which refers to the time interval between the start of fixation on the target image and the onset of the verbal response[3] (Gordon & Hoedemaker, 2016). Since EVS is about 250 ms longer than gaze duration, it is considered to include later processes related to speech articulation.

Araújo & Faísca (2020) manipulated the frequency and neighbourhood density of target words and found statistically significant interactions between group (dyslexia vs. control) and frequency, as well as between group and neighbourhood density. Moreover, the interaction between frequency and neighbourhood density suggested that neighbourhood density had a facilitating effect only for low-frequency words, affecting both dyslexic and control groups similarly. Individuals with dyslexia were simply slower on selected measures compared to the control group. The authors interpreted these results as evidence of suboptimal mapping of phonological representations onto articulatory commands (necessary for the naming task) in dyslexia. Since no impairment was found at the level of lexical access in individuals with dyslexia (which would have been indicated by differences between gaze duration and EVS compared to the control group), the authors considered these results as confirmation of the phonological deficit theory.

Huettig & Brouwer (2015) found slower anticipatory eye movements in individuals with dyslexia. In their study, the target image could be predicted based on the gender of the article in Dutch (*het* or *de*). The delay in anticipatory eye movements in individuals with dyslexia was interpreted by the authors as supporting the claim that literacy – in terms of reading and writing proficiency - af-

[3] In fact, the authors measured EVS from the end of the last fixation to the onset of the verbal response, which they referred to as *temporal offset-EVS*. Typically, EVS is measured from the beginning of the gaze at the relevant area of interest to the onset of the verbal response.

njem dolazećeg govornog inputa, tj. da pismenost mijenja fonološke reprezentacije i da one, budući da sadrže više detalja, postaju efikasnije u fonološkoj obradi.

U ranim danima mjerenja pokreta oka paradigma čitanja dala je više negativne nego pozitivne nalaze u pogledu traženja uzroka disleksije. Tako Black i sur. (1984) u elektro-okulografskoj studiji čitanja pokazuju da same promjene u pokretima očiju u djece s disleksijom ne mogu objasniti deficit opovrgavajući tako studiju Georgea Pavlidisa koji je upravo u promjenama sakadičkih pokreta kod djece s disleksijom, i to ne samo na zadacima čitanja, nego i u zadacima praćenja pogledom vidio „ključ" disleksije, tj. njegov „središnji deficit" (Pavlidis, 1981). Uz sva ograničenja tih ranih studija implikacija je rezultata Blacka i suradnika da se uzrok deficita treba tražiti na kognitivnoj razini, tj. na razini obrade informacija.

Novije studije koje nastoje pokazati deficit na fonološkoj razini najčešće se koriste rečenicama u kojima su ciljne riječi eksperimentalno manipulirane na fonološkoj razini, kao što je to u Blythe i sur. (2020), studija u kojoj su uspoređivali vremena čitanja rečenica, broj fiksacija, vjerojatnost preskakanja riječi i broj regresija u skupini odraslih i skupini adolescenata s disleksijom (i odgovarajućim kontrolnim skupinama). Ciljne riječi bile su grupirane u tri uvjeta: točno napisane (npr. *church*), pseudohomofoni (npr. *cherch*) i pseudoriječi (npr. *charch*). Osim što su obje skupine s disleksijom pokazale dulje vrijeme čitanja, nešto veći broj regresija i manju vjerojatnost preskakanja, lokalne mjere, tj. trajanje prve fiksacije na ciljnu riječ pokazale su da su se osobe s disleksijom u obje grupe značajno dulje zadržavale na pseudoriječima u odnosu na točno napisane riječi, a sve su skupine sudionika pokazale „prednost pseudohomofona" u odnosu na pseudoriječi. Iz takvih rezultata autori zaključuju da se u skupinama sudionika s disleksijom odvija procesno skuplje rekodiranje pseudohomofona u odnosu na kontrolu. Budući da se to rekodiranje odvija na fonološkoj razini (jer je takav zadatak), takvi su rezultati konzistentni s teorijom fonološkog deficita.

Drugačiju logiku istraživanja primijenili su Trauzettel-Klosinski i sur. (2002). Sudionicima su

fects the prediction of upcoming spoken input. In other words, literacy changes phonological representations, making them more detailed and thus more efficient in phonological processing.

In the early days of eye-tracking, the reading paradigm produced more negative than positive findings regarding the causes of dyslexia. For instance, in an electro-oculography study of reading, Black et al. (1984) demonstrated that changes in eye movements alone in children with dyslexia could not explain the deficit, thus refuting George Pavlidis's claims. Pavlidis (1981) observed that the "key" to dyslexia (i.e., its "central deficit") was in the saccadic movement differences in children with dyslexia, not only in reading tasks, but also in gaze-following tasks. Despite the limitations of these early studies, the result of Black et al. (1984) imply that the cause of the deficit should be sought at the cognitive level, i.e., in information processing.

More recent studies attempting to demonstrate deficits at the phonological level often use sentences in which target words are experimentally manipulated at the phonological level, as seen in Blythe et al. (2020). Their study compared reading times, fixation counts, word-skipping probabilities, and regression counts between a group of adults and adolescents with dyslexia, as well as their respective control groups. The target words were categorised into three conditions - correctly spelled words (e.g., *church*), pseudohomophones (e.g., *cherch*), and pseudowords (e.g., *charch*). While both dyslexic groups showed longer reading times, slightly more regressions, and a lower probability of skipping words, local measures, such as the first fixation duration on the target word, revealed that individuals with dyslexia fixated significantly longer on pseudowords than on correctly spelled words. All participant groups exhibited a "pseudohomophone advantage" over pseudowords. Based on these results, the authors concluded that individuals with dyslexia engage in more cognitively demanding phonological recoding of pseudohomophones than controls. Since this recoding occurs at the phonological level (due to the nature of the task), these findings align with the phonological deficit theory.

A different research approach was taken by Trauzettel-Klosinski et al. (2002). Participants dali dva zadatka, imenovanje piktograma i čitanje teksta. Ako se pretpostavlja deficit u pokretima očiju, očekuju se slični rezultati, tj. slične razlike između skupine djece (starosti 12-15 godina) na oba zadatka – s tim da imenovanje piktograma ne zahtijeva dekodiranje grafema u foneme. Dobivene razlike u zadacima sugeriraju upravo deficit na fonološkoj, a ne okulomotornoj razini.

Kognitivni ili deficit obrade informacija kao pozadinu disleksije vide i Stella i Engelhardt (2019). S obzirom na interes prema sintaktičkoj obradi u osoba s disleksijom, tj. slabijim rezultatima na testovima razumijevanja rečenice, autori problematiziraju dva teorijska modela, hipotezu verbalne efikasnosti i hipotezu sinkronizacije koje obje sadrže nedostatak dekodiranja riječi u osoba s disleksijom kao središnji pojam. Razlika je u tome što, prema prvoj hipotezi, taj nedostatak dovodi do nedostatka na višim razinama obrade (rečenica, tekst), dok je prema drugoj taj nedostatak posljedica nedostatka automatizacije, zbog čega su osobe s disleksijom sporije i moraju uložiti veći kognitivni napor.

Podražaje su činile dvosmislene rečenice (s odgovarajućim nedvosmislenim rečenicama u drugom uvjetu). Nakon rečenice bi slijedilo pitanje razumijevanja, npr. '*While Anna dressed the baby that was small and cute played on the bed'* (dvosmislena) i '*While Anna dressed, the baby that was small and cute played on the bed*'[4] s pitanjem je li Anna obukla dijete.

Osobe s disleksijom imale su dulje vrijeme čitanja, ali i dulje mjere prvog prolaza (engl. *first-pass*), a posebno na dvosmislenim rečenicama. Imali su više regresija, što pokazuje pojačanu tendenciju ka reanalizi. Ipak, kad se radi o razumijevanju rečenica (točnosti odgovora), te su se razlike izgubile kad se za kovarijatu, tj. prateću

[4] U hrvatskome je teško postići dvosmislenost na taj način, budući da bi se dvosmislena rečenica mogla prevesti na dvije rečenice koje ne sadrže dvosmislenost s time da jedna nije gramatična: Dok se Anna oblačila, dijete koje je bilo malo i slatko, igralo se na krevetu, i *Dok je Anna oblačila dijete koje je bilo malo i slatko igralo se na krevetu. Budući da je dijete objekt zavisne rečenice, nije subjekt glavne, ali to sudionik otkriva tek kad dođe do riječi *played*. Negramatičnost je posve očita ako se *baby* prevede s „beba“.

were given two tasks: pictogram naming and text reading. If an eye movement deficit were present, similar differences between the two groups (children aged 12-15 years) would be expected in both tasks, considering that pictogram naming does not require grapheme-to-phoneme decoding. However, the observed differences in task performance suggest a deficit at the phonological, rather than the oculomotor level.

Cognitive or information-processing deficits are also proposed to be underlying causes of dyslexia by Stella and Engelhardt (2019). Given the interest in syntactic processing in individuals with dyslexia -who tend to perform poorly on sentence comprehension tests - the authors examined two theoretical models: the verbal efficiency hypothesis and the synchronization hypothesis. Both models conceptualise word decoding deficits as central to dyslexia, but they differ in their implications. The first hypothesis suggests that decoding deficits lead to impairments at higher levels of processing (sentence, text comprehension), while the second posits that the deficit results from a lack of automatization, making individuals with dyslexia slower, thus, requiring greater cognitive effort.

The stimuli in their study consisted of ambiguous sentences (with corresponding unambiguous sentences in another condition). After reading a sentence, participants answered a comprehension question. For example, here is the ambiguous sentence: '*While Anna dressed the baby that was small and cute played on the bed.'*, and here is the unambiguous sentence: '*While Anna dressed, the baby that was small and cute played on the bed.*[4]

[4] In Croatian, it is difficult to achieve ambiguity in this way because the ambiguous sentence are translated into two sentences that do not contain ambiguity, with one of them being ungrammatical: '*Dok se Anna oblačila, dijete koje je bilo malo i slatko igralo se na krevetu'* ("While Anna was getting dressed, the child who was small and cute was playing on the bed") and '*Dok je Anna oblačila dijete koje je bilo malo i slatko igralo se na krevetu'* ("While Anna was dressing the child who was small and cute was playing on the bed"). Since "the child" is the object of the subordinate clause, it is not the subject of the main clause, but the participant only discovers this upon reaching the word '*played'*. The ungrammaticality becomes entirely evident if '*baby'* is translated as '*beba'* due to the differences in accusative case endings (-a and -u).

varijablu uzme rezultat na testu radnog pamćenja. Autori stoga slabost osoba s disleksijom u sintaktičkoj obradi tumače ograničenjima u radnom pamćenju koje smatraju posljedicom nedostatka dekodiranja riječi. Ti su rezultati, dakle, konzistentni s hipotezom verbalne efikasnosti.

Daleko veći broj istraživanja disleksije pomoću metode mjerenja pokreta oka oslanja se na – ili nastoji dokazati - „ne-lingvističke" teorije disleksije. Ta je pristranost razumljiva s obzirom na to da (1) sama metoda daje izravan uvid u promjene u pokretima očiju i (2) te se promjene mogu tumačiti nedostatkom na biološkoj razini obrade vidnog signala, čime se objašnjavaju deficiti na višoj, kognitivnoj razini. Drugim riječima, deficiti na kognitivnoj (jezičnoj, fonološkoj) razini, kako oni objašnjavaju opažene podatke, reduciraju se na jednostavne biološke (neuralne) mehanizme okulomotorne kontrole ili obrade vidnog signala. U takvom teorijskom okviru fonološki su deficiti sekundarni i posljedica su nedostataka u kontroli pokreta oka, vizualnom ili deficitu pažnje, što otežava prepoznavanje riječi i njihovo fonološko kodiranje. Na kraju, te je hipoteze lakše provjeravati na čitanju teksta, pa se time postiže veća ekološka valjanost studija.

Starija studija (Eden i sur., 1993) otkriva deficite u okulomotornoj kontroli (nestabilnost fiksacija, manje amplitude u pokretima vergencije, razlike u odnosu na kontrolu u zadacima praćenja pogledom), deficite koji se ne mogu objasniti samo jezičnim problemima. Različit „profil pokreta oka" kod osoba s disleksijom nalaze Franzen i sur. (2021), točnije, dulje fiksacije, manju amplitudu sakada uz njihovu veću varijabilnost, što autori tumače nedostatkom u „strategiji vizualnog uzorkovanja", tj. tvrde da se nedostatak sastoji od obrade manje sadržaja istovremeno i sporošću u uzimanju informacija iz teksta. Uz to, naročitu pozornost pridaju „devijacijama u smjeru" (engl. *directional deviations*), tj. sakadama koje nisu tipične u čitanju (npr. odstupanja u okomitom smjeru, što signalizira da se osoba izgubila u tekstu). Kao posebnu osobitost primjećuju da su te okomite sakade većinom prema dolje, dok su u kontrolnoj skupini one bile prema gore.

Here is the question posed by the participants: '*Did Anna dress the baby?'*.

Individuals with dyslexia showed longer reading times and prolonged first-pass durations, particularly in ambiguous sentences. They also had more regressions, indicating a stronger tendency for reanalysis. However, differences in sentence comprehension (accuracy of responses) disappeared when working memory test scores were controlled as a covariate. The authors thus interpreted the syntactic processing weaknesses in individuals with dyslexia as being a function of working memory limitations, which they consider a consequence of word decoding deficits. These results are consistent with the verbal efficiency hypothesis.

A substantially larger number of studies on dyslexia using the eye-tracking method rely on, or seek to prove, "non-linguistic" theories of dyslexia. This bias is understandable given that (1) the method itself provides direct insight into changes in eye movements, and (2) these changes can be interpreted as deficits at the biological level of visual signal processing, which in turn explain deficits at the higher cognitive level. In other words, deficits at the cognitive level (linguistic, phonological), as explained by these theories in the observed data, are reduced to simple biological (neural) mechanisms of oculomotor control or visual signal processing. Within such a theoretical framework, phonological deficits are secondary and result from deficiencies in eye movement control, visual processing, or attention deficits, which hinder word recognition and phonological encoding. Finally, these hypotheses are easier to test in text-reading tasks, thus enhancing the ecological validity of the studies.

In earlier work, Eden et al. (1993) identified deficits in oculomotor control (fixation instability, reduced vergence movement amplitude, and differences compared to controls in gaze-following tasks) that cannot be explained solely by linguistic problems. Franzen et al. (2021) observed a different *eye movement profile* in individuals with dyslexia, more specifically longer fixations, and smaller saccade amplitudes with greater variability, which the authors interpret as a deficiency in the *visual sampling strategy*. They argue that this deficiency consists of processing lesser amounts

Studija slučaja 15-godišnjaka s teškom disleksijom (Pensiero i sur., 2013) upućuje na subkliničke promjene u sakadičkim pokretima, prekinutim sakadama (tj. sakadama koje „podbacuju“) i nestabilnim fiksacijama (tj. fiksacijama kod kojih jedno oko zaostaje za drugim u fiksiranju na cilj, odnosno binokularna nestabilnost, ili jednostavna nestabilnost koja se sastoji od kratkih nevoljnih sakada dok se oko fokusira na nepomični cilj). Na temelju tih rezultata autori zaključuju kako bar u nekim slučajevima disleksije nije stvar u otežanoj interpretaciji vizualnih podataka, nego u promjenama u okulomotornim neuralnim putovima.

Tiadi i sur (2016) na temelju usporedbe fiksacija i sakada u djece s disleksijom (7-15 godina starosti) s kontrolnim skupinama koje su odabrane po kronološkoj i „čitalačkoj“ dobi, nalaze slabost djece s disleksijom da inhibiraju neželjene sakade, što povezuje simptome disleksije s onima u djece s ADHD-om. S obzirom na razlike u skupinama, autori sugeriraju kako se biološki temelj disleksije najvjerojatnije može locirati u nezrelosti gornjeg kulikula. I konačno, Stein (2001) vidi uzroke disleksije u teškoćama u razvoju magnocelularnog sustava, što se u vizualnoj domeni očituje u smanjenoj osjetljivosti na pokret, nestabilnost u binokularnoj fiksaciji, što dovodi do teškoća u vizualnoj lokalizaciji. Zbog toga osobe s disleksijom ne mogu pratiti tekst. Također, Stein navodi nižu osjetljivost osoba s disleksijom na promjene u frekvenciji i amplitudi zvuka, što otežava razlikovanje fonema. Obrada vremenskih podataka (promjene u zvuku ili u vidnom polju) povezuje se s velikim stanicama u svim senzornim i motornim sustavima i s malim mozgom, a genetski se uzrok (na kromosomu 6) smatra uzrokom razvojnih promjena na magnocelularnim sustavima. Budući da se radi o područjima koja obrađuju brze promjene, nisu osjetljiva na oblik podražaja, a stanice imaju mala receptivna područja, povezanost s čitanjem je posredna, preko vizualne pažnje i prostorne integracije, funkcija koje se mogu smatrati važnima za čitanje. Zato se potvrde magnocelularne teorije disleksije traže baš na zadacima vizualne pretrage. Budući da nemaju sve osobe s disleksijom teškoće u percepciji

of information at a time and slower extraction of information from the text. Additionally, they noticed *directional deviations*, i.e., saccades that are atypical in reading (e.g., vertical deviations indicating that the person has lost their place in the text). A particularly notable feature is that these vertical saccades corresponded to downward deviations in the dyslexic group and upward deviations in the control group.

A case study of a 15-year-old with severe dyslexia (Pensiero et al., 2013) points to subclinical changes in saccadic movements, interrupted saccades (i.e., under-shooting saccades), and unstable fixations (i.e., fixations where one eye lags behind the other in targeting the fixation point, indicating binocular instability, or simple instability involving short involuntary saccades while the eye focuses on a stationary target). Based on these results, the authors conclude that, at least in some cases of dyslexia, the issue is not merely in the interpretation of visual data, but in changes within the neural pathways responsible for oculomotor control.

Tiadi et al. (2016) compared fixations and saccades in children with dyslexia (aged 7-15 years) with control groups matched for chronological and “reading” age and found that children with dyslexia struggle to inhibit unwanted saccades, linking dyslexia symptoms to those in children with ADHD. Given the group differences, the authors suggest that the biological basis of dyslexia tends to be linked to immaturity of the superior colliculus. Finally, Stein (2001) attributes dyslexia to difficulties in the development of the magnocellular system, which manifests as reduced motion sensitivity and instability in binocular fixation in the visual domain, leading to difficulties in visual localisation. As a result, individuals with dyslexia struggle to track text. Stein also noted lower sensitivity to changes in sound frequency and amplitude in dyslexic individuals, making phoneme differentiation more difficult. Temporal data processing (changes in sound or the visual field) is linked to large cells across sensory and motor systems and the cerebellum, with the genetic cause (on chromosome 6) believed to determine developmental changes in magnocellular systems. Since these areas process rapid changes that are not sensitive to koherentnosti pokreta, Iles i sur. (2000) zadatak vizualne pretrage prikazuju trima skupinama sudionika: kontrolnoj skupini, osobama s disleksijom s problemima u percepciji pokreta i bez njih (srednja dob sudionika bila je 25 godina). Budući da su obje skupine osoba s disleksijom pokazale slične promjene u odnosu na kontrolu, samo su one bile izraženije kod skupine s problemima u percepciji pokreta, takvi se rezultati mogu tumačiti kao potvrda magnocelularne teorije disleksije. S druge strane, rezultati dobiveni u studiji Wrighta i sur. (2012), u kojoj se također upotrebljavao zadatak vizualne pretrage, pokazale su vrlo malu razliku između djece s disleksijom i kontrolne skupine, što su autori protumačili značajnim preklapanjem između skupina. Autori su dodatno podijelili skupinu djece s disleksijom na one koje imaju i koje nemaju magnocelularni deficit. Ako se usporede vremena otkrivanja vizualnog cilja u svim trima skupinama, nema razlike među skupinama, što autori tumače nezavisnošću slabosti u vizualnoj pretrazi od magnocelularnog deficita u disleksiji.

Hutzler i sur. (2006) smatraju da se okulomotorni deficit ili deficit u vizualnoj pretrazi može pokazati na dvama zadacima: na zadatku „obrade niza“ (engl. *string-processing task*) i na zadatku čitanja pseudoriječi. Budući da na zadatku obrade niza nisu potrebni viši psiholingvistički procesi, kao što su konverzija grafema u fonem, nego samo identifikacija slova, razlika u skupinama (disleksija vs. kontrola) na dvama zadacima indikativna je za pozadinu disleksije: okulomotorni deficit i deficit vizualne percepcije vjerojatniji je ako osobe s disleksijom pokažu slabije rezultate u oba zadatka. Ako su osobe s disleksijom slične kontrolnoj skupini na zadatku obrade niza, a lošiji na zadatku čitanja pseudoriječi, uzrok disleksije valja tražiti na višim psiholingvističkim razinama obrade. Budući da nisu nađene razlike između osoba s disleksijom i kontrolne skupine na zadatku obrade niza, autori zaključuju da osobe s disleksijom nemaju teškoća u točnoj percepciji slova, što upućuje na teškoće na višim razinama obrade. Na zadatku praćenja pokretnog cilja osobe s disleksijom pokazivale su odstupanja u kontroli sakada, ali autori smatraju da taj deficit nije

stimulus shape, and they contain cells with small receptive fields, the connection to reading is indirect - through visual attention and spatial integration, both of which are important for reading. Therefore, support for the magnocellular theory of dyslexia is primarily sought in visual search tasks.

Since not all individuals with dyslexia exhibit difficulties in motion coherence perception, Iles et al. (2000) presented a visual search task to three participant groups: a control group and two dyslexic groups, one with and one without motion perception problems (mean age: 25 years). Since both dyslexic groups exhibited similar differences compared to the controls, with the effects being more pronounced in the group with motion perception problems, the results were interpreted as supporting the magnocellular theory of dyslexia. On the other hand, findings from Wright et al. (2012), who also used a visual search task, showed minimal differences between dyslexic children and controls, which the authors attributed to significant overlap between the groups. They further divided the dyslexic group into those with and without a magnocellular deficit. When comparing visual target detection times across all three groups, no differences emerged, leading the authors to conclude that visual search difficulties in dyslexia are independent of a magnocellular deficit.

Hutzler et al. (2006) argued that oculomotor or visual search deficits can be examined through two tasks: a “string-processing” task and a pseudoword reading task. Since the string-processing task focuses only on letter identification and does not require higher psycholinguistic processes (such as grapheme-to-phoneme conversion), differences between dyslexic and control groups across both tasks would indicate the underlying nature of dyslexia. If dyslexic individuals perform worse on both tasks, an oculomotor or visual perception deficit is more likely. However, if dyslexic individuals perform similarly to controls in the string-processing task, but worse in pseudoword reading, then the cause of dyslexia lies in higher psycholinguistic processing. Since no differences were found between the dyslexic and control groups in the string-processing task, the authors conclude that dyslexic individuals do not struggle with accurate letter perception, dovoljno jak da utječe na percepciju i okulomotornu kontrolu u čitanju.

Iako istraživanja disleksije mjerenjem pokreta oka općenito naglašavaju promjene u pokretima oka kod osoba s disleksijom, te se promjene mogu tumačiti u svjetlu „lingvističkih“ i „ne-lingvističkih“ teorija. Zamjerka je prvima cirkularnost (usp. Frith, 1999): problem je u fonološkim reprezentacijama jer su osobe s disleksijom lošije na zadacima koji sadrže fonološku komponentu. Nedostatak konzistentnih nalaza kao i konzistentnost s alternativnim objašnjenjima (usp. Huettig i Brouwer, 2015), tj. činjenica da promjene u pokretima očiju mogu biti posljedica, a ne uzrok kognitivnih deficita s velikom individualnom varijabilnošću ograničenja su „ne-lingvističkih“ teorija disleksije, kako se one istražuju metodom mjerenja pokreta oka.

Trijaža i dijagnostika

Pretraga baza *Web of Science* i *Scopusa* dala je 53 rada u kojima se mjerenje pokreta oka upotrebljava za trijažu ili dijagnostiku disleksije. U pravilu se radi o kratkom zadatku čitanja teksta nakon kojeg se dobiveni rezultati mjerenja pokreta oka obrađuju algoritmom strojnog učenja. Važan je motiv upotrebe metode mjerenja pokreta oka u trijaži ili dijagnostici naći metodu pouzdaniju od onih koje se temelje na testiranju fonološke svjesnosti i brzog imenovanja (RAN). Te su metode pokazale tipičnu točnost od 70 do80 %. Pennington i sur. (2012) tako u studiji, koja ima teorijski motiv u testiranju modela, ali se temelji na teorijskoj utemeljenosti pojedinih metoda dijagnostike, izvještavaju o 75 % objašnjavanja varijance i o visokoj specifičnosti, ali i niskoj osjetljivosti instrumenata koji se temelje na fonološkoj svjesnosti i RAN-u. Problem klasifikacije osoba s obzirom na to imaju li ili nemaju disleksiju težak je već zbog toga što se ona od samih početaka njezina proučavanja[5] ne smatra binarnim poremećajem, nego kontinuumom (Peterson i Pennington, 2012). Taj se problem u suvremenim studijama, koje se temelje na mjerenju pokreta oka, kako je spomenuto, nastoji riješiti razvojem i procjenom

[5] Točnije, od Morgana (1896) i Ortona (1925).

pointing instead to difficulties at higher levels of processing. In a moving-target tracking task, dyslexic individuals exhibited deviations in saccade control, but the authors argued that this deficit is not strong enough to impact perception and oculomotor control in reading.

Although eye-tracking research on dyslexia generally emphasises changes in eye movements among dyslexic individuals, these changes can be interpreted in the light of both “linguistic” and “non-linguistic” theories. A major criticism of the former is circular reasoning (see Frith, 1999): the issue lies in phonological representations because dyslexic individuals perform worse on tasks with a phonological component. The lack of consistent findings, as well as the plausibility of alternative explanations (see Huettig & Brouwer, 2015) - the fact that eye movement changes may be a consequence rather than a cause of cognitive deficits - along with significant individual variability point to the limitations of “non-linguistic” theories of dyslexia as studied through eye-tracking methodology.

Screening and diagnostics

A review of the Web of Science and Scopus databases identified 53 studies in which eye movement measurement was used for the screening or diagnosis of dyslexia. An important motivation for using eye movement measurement in screening or diagnosis is to find a method that is more reliable than those based on phonological awareness testing and rapid automatized naming (RAN). These methods have shown a typical accuracy of 70-80%. In a study theoretically motivated by testing models and based on the theoretical validity of different diagnostic methods, Pennington et al. (2012) reported 75% explained variance and high specificity, but low sensitivity for instruments based on phonological awareness and RAN. The problem of classifying individuals based on whether they have dyslexia is challenging because dyslexia has not been considered a binary disorder from the outset[5], but rather a continuum (Peterson & Pennington, 2012).

[5] From the times of Morgan (1896) and Orton (1925), to be more precise.

uspješnosti algoritama strojnog učenja koji na uzorcima teksta što je moguće točnije automatski razvrstavaju sudionike na one s disleksijom i one bez nje. U načelu, budući da je u takvim istraživanjima fokus na dokazivanju uspješnosti algoritma, istraživač ima podatke o tome tko ima dijagnozu disleksije, a tko ne, samo to, naravno, nije poznato algoritmu strojnog učenja (tj. poznato je samo u procesu učenja, tj. treniranja). Takav način otkrivanja disleksije ne mora se nužno temeljiti na podacima mjerenja pokreta oka, nego na bilo kojoj metodi koja daje numeričke vrijednosti, npr. na tipkanju na računalu dok se osobi mjeri signal eeg-a, (Perera i sur., 2018) ili, češće, obradi rezultata internetskih igara (usp. Rello i sur., 2018). Igru su, *Dytective*, Rello i sur. razvili s obzirom na pogreške koje osobe s disleksijom najčešće rade, tj. s obzirom na kognitivne vještine povezane s disleksijom kao što su radno pamćenje, izvršne funkcije, vizualna percepcija, jezična obrada. U *Dytectivu* igrač kao detektiv rješava razne zadatke, npr. prepoznaje pseudoriječi među distraktorima ili prepoznaje semantičku ili sintaktičku grešku (npr. u rečenici "*Smoking is prohibited of the entire aircraft*" u kojoj je prijedlog *in* zamijenjen s *of*).

Algoritam strojnog učenja na podacima mjerenja pokreta oka upotrijebljen je u Rello i Ballesteros (2015) na podacima 97 osoba od kojih je 48 imalo dijagnosticiranu disleksiju. U studiji su uzeti sudionici vrlo širokoga dobnog raspona od 11 do 54 godine starosti. Podaci su prikupljeni na čitanju 12 tekstova napisanih različitim fontovima, uključujući i font namijenjen osobama s disleksijom (*OpenDyslectic*) i font koji *British Dyslexia Association* preporučuje osobama s disleksijom (*Verdana*). Upotrijebljen je binarni klasifikator LIBSVM koji koristi metodu SVM (*Support Vector Machine*). Radi se o algoritmu nadziranog učenja (engl. *supervised learning*) koji trenira model na označenim podacima (tj. trenira se na podacima označenima za pripadnost kategoriji, pa nove podatke klasificira prema naučenim obrascima). Postignuta je točnost od ≈80 % na odlikama podataka koje su se pokazale u najvećoj mjeri prediktivnima, a to su ukupno vrijeme čitanja, prosječno trajanje fiksacija i dob sudionika.

In contemporary studies using eye movement measurement, this issue is addressed by developing and evaluating the effectiveness of machine learning algorithms that automatically classify participants as dyslexic or non-dyslexic based on text samples. In principle, since these studies focus on proving the algorithm's effectiveness, researchers have information about individuals with and without a dyslexia diagnosis - though, of course, this information is not known to the machine learning algorithm (except during the training phase). This approach of detecting dyslexia does not necessarily have to rely on eye movement measurement data: for example, it can be based on keystroke dynamics while measuring electroencephalographic EEG signals (Perera et al., 2018) or, more commonly, on processing results from online games (see Rello et al., 2018). Rello et al. (2018) developed the game *Dytective* based on the types of errors frequently made by individuals with dyslexia, focusing on cognitive skills associated with dyslexia such as working memory, executive functions, visual perception, and language processing. In *Dytective*, the player takes on the role of a detective solving various tasks, such as identifying pseudowords among distractors or detecting semantic or syntactic errors (e.g., in the sentence *"Smoking is prohibited of the entire aircraft,"* where the preposition '*in'* is incorrectly replaced with '*of'*).

A machine learning algorithm applied to eye movement data was used in Rello and Ballesteros (2015). The data were collected from 97 individuals, 48 of whom had been diagnosed with dyslexia. The study included participants from a wide age range, from 11 to 54 years old. The reading data were collected based on 12 texts written in different fonts, including one designed for individuals with dyslexia (OpenDyslexic) using the font recommended by the British Dyslexia Association (Verdana). The binary classifier LIBSVM, which utilises the Support Vector Machine (SVM) method, was applied. This is a supervised learning algorithm that trains a model on labelled data (i.e., it learns from data labelled with category membership and then classifies new data based on learned patterns). An accuracy of approximately 80% was achieved based on the most predictive features, namely total reading time, average fixa-

Neke odlike, tj. neke varijable koje daje uređaj za mjerenje pokreta oka, kao što su broj fiksacija na neku točku, tj. područje (engl. *number of visits*) i ukupan broj fiksacija pokazale su se prediktivne, uzete same za sebe, ali su redundantne u modelu.

Polazeći od rane intervencije kao najboljeg načina podrške djeci s disleksijom, Nilsson Benfatto i sur. (2016) u svoju su studiju uključili djecu 9-10 godina starosti, i to njih 97 koji su pripadali visokorizičnoj skupini i njih 88 koji su pripadali skupini niska rizika za disleksiju. Djeca s visokim rizikom disleksije definirana su kao ona koja su postigla rezultate ispod 5. percentila na punoj kohorti testova dekodiranja riječi i imala problema u učenju čitanja, na temelju procjene učiteljice (dakle, nisu imala dijagnosticiranu disleksiju). Također, nisu uzete u obzir razlike u razini čitanja i drugih kognitivnih vještina i kvocijenta inteligencije, i to zato što autori smatraju da se disleksija može javiti na cijeloj skali IQ-a. Sudionici su čitali tek jednu stranicu od osam linija teksta, a podaci su kao i u Rello i Ballesteros (2015) analizirani, tj. klasificirani pomoću SVM-a). Postignuta je visoka točnost klasifikacije (≈95 %) na velikom broju odlika, s tim se primijenilo rekurzivno micanje odlika iz modela budući da nema značajnog povećanja točnosti nakon više od 25 odlika. Točnost klasifikacije od 95 % (Nilsson Benfatto i sur., 2016) najviši je postotak postignut pomoću SVM-a.

Iz „sirovog“ signala uređaja (x, y koordinata pogleda za svakih 10 ms (koristili su se uređajem od 100 Hz) dobili su velik broj mjera (progresivne i regresivne sakade, progresivne i regresivne fiksacije, tj. koliko je dugo trajala fiksacija koja je slijedila nakon progresivne, tj. regresivne sakade, broj fiksacija, duljina fiksacija, postotak regresija itd.), tj. analizirale su se prostorne i vremenske odlike signala. Autori nalaze da su se vodoravne odlike pokazale važnije za klasifikaciju od okomitih, što je očekivano s obzirom na to da se u švedskome čita slijeva nadesno. Kad je čitanje bilo prekinuto, odlike koje su se odnosile na okomitu dimenziju u čitanju pokazale su se diskriminatorne, što je rezultat konzistentan sa spomenutim rezultatom u Frenzen i sur. (2021).

tion duration, and participant age. Some features, such as the number of fixations on a specific point or area (number of visits) and the total number of fixations, were predictive when considered individually, but were redundant in the model.

Starting from the premise that early intervention is the best way to support children with dyslexia, Nilsson Benfatto et al. (2016) conducted a study including 97 children (aged 9-10 years) who belonged to a high-risk group for dyslexia and 88 children who belonged to a low-risk group for dyslexia. Children at high risk of dyslexia were defined as those who scored below the 5th percentile on a full cohort of word decoding tests and had reading difficulties based on their teacher's assessment (i.e., they had not been formally diagnosed with dyslexia). Differences in reading level, other cognitive skills, and IQ were not considered because the authors argued that dyslexia could occur across the entire IQ spectrum. Participants read only a single page of text with eight lines, and the data, similar to Rello and Ballesteros (2015), were analysed and classified using SVM. A high classification accuracy (≈95%) was achieved across a large number of features, with recursive feature elimination applied to the model since accuracy did not significantly increase beyond 25 features. The classification accuracy of 95% (Nilsson Benfatto et al., 2016) is the highest percentage achieved using SVM.

From the "raw" signal of the device (x, y gaze coordinates recorded every 10 ms using a 100 Hz device), a large number of measures were extracted, including progressive and regressive saccades, progressive and regressive fixations (i.e., the duration of a fixation following a progressive or regressive saccade), number of fixations, fixation duration, percentage of regressions, and so on. In other words, both spatial and temporal features of the signal were analysed. The authors found that horizontal features were more important for classification than vertical ones, which is expected given that reading in Swedish proceeds from left to right. When reading was interrupted, features related to the vertical dimension in reading were found to be discriminative, which is consistent with earlier findings by Frenzen et al. (2021).

U Vajs i sur. (2022) autori se koriste različitom bojom podloge, ali i da bi kodirali brzinu čitanja, pa su tako kodirane slike s pokretima očiju djece koja su čitala pripovijetku „*Sv. Sava i seljak bez sreće*“ analizirane konvolucijskom neuralnom mrežom (zahvaljujući tome što su dijelovi slike pretvorene u numeričke vrijednosti koje kodiraju položaj i brzinu). Najbolja postignuta točnost klasifikacije na 30 djece (15 disleksija, 15 kontrola) bila je 87 %, što je dobar rezultat s obzirom na manji broj sudionika i relativno staru opremu (SMI 120Hz RED-M).

Konvolucijske neuralne mreže upotrijebljene su za otkrivanje odlika signala s uređaja za mjerenje pokreta oka i za njihovu klasifikaciju u Nerušil i sur. (2021). Njihov je uzorak činilo 185 djece stratificirane prema riziku disleksije. Zadatak je činilo 10 rečenica prosječne duljine 4,6 riječi po retku. Postignuta je vrlo visoka točnost klasifikacije, tj. stopa točno pozitivnih (osjetljivost) bila je 96,6 % i to na signalu s minimalno predobrade i s jednostavnijim postupkom učenja, što bi u budućnosti trebalo imati prednost u korisničkim aplikacijama. Autori naglašavaju važnost stope točno pozitivnih u dijagnostici, a sposobnost neuralne mreže da implicitno nauči odlike signala i analiza koja se temelji na reprezentaciji veličine spektra (engl. *magnitude spectrum representation*) omogućuje promatranje cijele putanje pogleda (engl. *scanpath*), što se pokazalo uspješnim u analizi u kojoj postoje velike razlike u brzini čitanja od sudionika do sudionika (reprezentacija veličine spektra eliminira efekt vremena, tj. signal pomoću Fourierove analize promatra u frekvencijskoj domeni u smislu kvantifikacije promjena u frekvenciji sakada ili fiksacija).

Konačno, Pawel Kasprowski (Kasprowski, 2024) ne upotrebljava nikakvu predobradu podataka s uređaja za mjerenje pokreta oka, nego se koristi „sirovim podacima“, tj. samo koordinatama smjera pogleda (x, y) iz milisekunde u milisekundu (u analizi je taj skup podataka reduciran na 10 Hz tako da se uzela vrijednost svake stote vrijednosti). Ti su podaci činili dijagrame samo-sličnosti pogleda (engl. *Gaze Self Similarity Plots, GSSP*, Kasprowski i Katarzyna, 2017) koji mogu grafički i numerički prikazati bliskost u položaju

In Vajs et al. (2022), the authors used different background colours to encode reading speed. Eye movements from children reading the story “St. Sava and the Unlucky Peasant” were analysed using a convolutional neural network (CNN), with images coded for gaze position and velocity. The highest classification accuracy achieved for 30 children (15 with dyslexia, 15 controls) was 87%, which is a good result considering the small sample size and relatively old equipment (SMI 120Hz RED-M).

Convolutional neural networks were also used to detect features in eye-tracking signals and classify them in Nerušil et al. (2021). Their sample consisted of 185 children, stratified according to dyslexia risk. The task involved reading 10 sentences with an average length of 4.6 words per line. A very high classification accuracy was achieved, with a true positive rate (sensitivity) of 96.6% that was based on minimally pre-processed signals and a simpler learning procedure, which could be advantageous for future user applications. The authors emphasised the importance of the true positive rate in diagnostics and highlighted how CNNs can implicitly learn signal features. The analysis, based on magnitude spectrum representation, allows for the observation of the entire scan path, which proved successful in handling large differences in reading speed among participants (magnitude spectrum representation eliminates time effects by analysing the signal in the frequency domain using Fourier analysis to quantify changes in saccade and fixation frequency).

Finally, Pawel Kasprowski (Kasprowski, 2024) did not use any preprocessing of eye-tracking data, instead, he worked with “raw data”, i.e., only gaze direction coordinates (x, y) recorded millisecond by millisecond (this dataset was reduced to 10 Hz by selecting every 100th value). These data were transformed into Gaze Self-Similarity Plots (GSSP; Kasprowski & Katarzyna, 2017), which can visually and numerically represent gaze position similarities corresponding to fixations (clusters of x, y coordinates close in time) in a scan path. For example, they can show that in a sequence of 10 fixations, the third, fifth, and eighth are closer to each other than, say, the onoga što bi odgovaralo fiksacijama (skupinama x,y koordinata bliskima u vremenu) u nekoj putanji pogleda (npr. prikazuje da su u nekom nizu od 10 fiksacija treća, peta i osma blizu jedna drugoj od, npr. druge i šeste). Također, mogu se prikazati i regresije, jasni su obrasci pretraživanja i sl. Pomoću takvih prikaza konvolucijska neuralna mreža s četiri sloja razvrstala je rezultate mjerenja pokreta oka prikazanih kao individualni GSSP 36-oro sudionika s točnošću od 83,3 % (30 od 36 točno klasificiranih) tako da je svakome sudioniku dodijelila srednji indeks (*score*) u rasponu od 0 do 1, što odgovara vjerojatnosti da GSSP pripada osobi koja ima disleksiju. Ako se disleksija „dijagnosticirala" za vrijednost višu od 0,7, samo su tri osobe s disleksijom imale niži indeks, dok su tri osobe bez disleksije imale indeks viši od 0,7. Preciznost bi, dakle, bila , dakle, 0,83. Promjena vrijednosti indeksa na 0,725 dala je veću točnost i preciznost od ≈89 %, tj. 0,89. Daljnje povećavanje indeksa, na vrijednosti iznad 0,8 previše bi osoba s disleksijom svrstalo u skupinu bez nje, pa bi se točnost i preciznost smanjila. Takav pristup dobro odražava spomenutu nebinarnu narav disleksije i dobro održava ravnotežu između pravih i lažnih pozitivnih, što je važno za praktičnu primjenu predloženog algoritma.

Istraživanja koja se bave nalaženjem metoda trijaže ili dijagnostike disleksije fokusirana su na izradu najboljeg algoritma – često tek nekoliko postotaka boljeg od prethodnog, u pravilu pripadaju računalnim znanostima i ne sadrže mnogo logopedskih, a ni lingvističkih detalja. Ipak, napredak u razvoju algoritama strojnog učenja sugerira sve veću ulogu metode mjerenja pokreta oka upravo u ranom otkrivanju i dijagnostici disleksije.

Terapija i asistivna tehnologija

Metoda mjerenja pokreta oka našla je primjenu i u terapiji disleksije, i to na dva načina: prvo, kao alat za okulomotornu vježbu ili vježbu učenja i pamćenja, i drugo, kao alat za personaliziranu intervenciju. Taj alat u Bucci i sur., (2018) čini program s raznim zadacima (RAN, zadatak otkrivanja pokreta i Stroop) nakon kojih bi sudionici (djeca između šest i osam i pol godina) pročitala kratak tekst, Dahlovu priču Veliki nježni div.

second and the sixth. They can also represent regressions, search patterns, and so on. Using these representations, a four-layer CNN-classified eye-tracking result was represented as individual GSSPs for 36 participants with an accuracy of 83.3% (30 out of 36 correctly classified). Each participant was assigned a score between 0 and 1, corresponding to the probability that their GSSP belonged to a person with dyslexia. If dyslexia was "diagnosed" at a score above 0.7, only three individuals with dyslexia had a lower index, while three individuals without dyslexia had an index above 0.7. Precision was therefore 15/18, or 0.83. Adjusting the threshold to 0.725 resulted in a higher accuracy and precision of ≈89% (0.89). Increasing the threshold above 0.8 resulted in the categorisation of several dyslexic individuals into the non-dyslexic group, reducing accuracy and precision. This approach effectively reflects the non-binary nature of dyslexia and maintains a balance between true and false positives, which is crucial for practical applications of the proposed algorithm.

Research focused on developing triage or diagnostic methods for dyslexia aims to create the best algorithm that is often only slightly better than its predecessor and generally belonging to the field of computer science, thus, containing few speech therapy or linguistic details. Nevertheless, advancements in machine learning algorithms suggest an increasing role for eye-tracking measurement methods in the early detection and diagnosis of dyslexia.

Therapy and Assistive Technology

Eye-tracking has been applied in dyslexia therapy in two ways: first, as a tool for oculomotor exercises or exercises for learning and memory, and second, as a tool for personalised intervention. In Bucci et al. (2018), this tool consists of a programme with various tasks (RAN, motion detection task, and Stroop) followed by a reading task, Roald Dahl's The Big Friendly Giant. The study shows that eye-tracking can be used as an objective measure of changes in oculomotor patterns before and after training. The exercises improved children's visual and attention skills, leading to

Studija pokazuje kako se mjerenje pokreta oka može upotrijebiti kao objektivna mjera promjena u okulomotornim obrascima prije i nakon vježbe. Vježba na spomenutim zadacima unaprijedila je, nalaze autori, vizualne i sposobnosti pažnje, što je za posljedicu imalo bržu identifikaciju riječi. Naročita je prednost ovakvog uvježbavanja što su djeca vježbala kod kuće. U studiji su se upotrebljavale naočale, tj. uređaj za mjerenje pokreta oka bio je ugrađen u naočale (Eye Brain T2®, SuriCog s preciznošću od 0,25° i rezolucijom od 300 Hz, što je dovoljno za istraživanje čitanja).

U Syahputri i sur. (2022) uspoređivale su se dvije skupine djece između sedam i 10 godina s raznim teškoćama, ne samo disleksijom (teškoće iz spektra autizma, ADHD, posebne teškoće učenja, razvojne jezične teškoće i granične intelektualne teškoće). Sudionici, njih 53 slučajnim su izborom podijeljeni u dvije skupine, jednu koja je bila uključena u vježbe s mjerenjem pokreta oka temeljene na igricama i drugu, koja je bila uključena u „konvencionalne vježbe" s tim da su skupine bile ujednačene po dobi, spolu, godinama obrazovanja, dijagnozi i inicijalnim procjenama učenja, pamćenja i čitanja. Obje su skupine pokazale napredak izmjeren na testovima čitanja (razumijevanje, prisjećanje riječi); skupina uključena u konvencionalne vježbe pokazala je veći napredak u brzini čitanja. Skupina uključena u vježbe s mjerenjem pokreta oka postigla je veći napredak u učenju i pamćenju, posebno odgođenom prisjećanju i bila je brža u učenju. Uključivanje tako nehomogene skupine sudionika ipak se pokazalo kao ograničenje ove studije. Ona je ipak pokazala korist upotrebe metode mjerenja pokreta oka i u terapiji, polazeći od pretpostavke da su promjene u pokretima oka povezane s kognitivnim problemima, pa vježba pokreta oka može pozitivno utjecati na te probleme.

Mjerenje pokreta oka pokazalo se korisnim u terapiji disleksije i kao čitateljeva pomoć koja prati pokret oka (engl. *gaze.contingent reading aids*). U Schiavo i sur. (2021) autori ispituju asistivnu tehnologiju koja se temelji na audiovizualnoj integraciji tako da se koristi strojnim čitanjem naglas vođenim pokretom oka, čime se čitanje prilagođava brzini kojom čitač prelazi preko teksta.

faster word identification. A significant advantage of this training was that the children practiced at home. The study used glasses equipped with an eye-tracking device (Eye Brain T2®, SuriCog, with an accuracy of 0.25° and a resolution of 300 Hz, which is sufficient for reading research).

Syahputri et al. (2022) compared two groups of children (aged 7-10 years) with various difficulties, not just dyslexia (including autism spectrum disorders, ADHD, specific learning disabilities, developmental language disorders, and borderline intellectual disabilities). A total of 53 participants were randomly divided into two groups: one engaged in eye-tracking-based games and the other in "conventional exercises". The groups were matched for age, gender, years of education, diagnosis, and initial assessments of learning, memory, and reading. Both groups showed progress in reading tests (comprehension, word recall): the conventional exercises group showed greater improvement in reading speed, while the eye-tracking group showed greater improvement in learning and memory, particularly in delayed recall, and they were faster at learning. However, the inclusion of such a heterogeneous group of participants was a limitation of the study. Nevertheless, the study demonstrated the usefulness of eye-tracking in therapy, based on the assumption that changes in eye movements are linked to cognitive difficulties and that eye movement exercises can positively influence these difficulties.

Eye-tracking has also been useful as a reading aid that tracks eye movements (gaze-contingent reading aids). In Schiavo et al. (2021), researchers examined an assistive technology based on audiovisual integration, using machine-read aloud text controlled by eye movements, adjusting the reading speed to match the reader's pace across the text. This system helps children follow the text with their eyes while listening. The system was tested on 40 children aged 8-10 years, including 20 diagnosed with dyslexia. Results showed a 24% improvement in standardised comprehension tests, with the most significant improvements seen in children with poor reading skills (9 out of 20).

Tako program pomaže djetetu da slijedi tekst okom dok ga sluša. Taj je sustav provjeren na 40 djece 8-10 godina starosti; dvadesetoro je djece imalo dijagnosticiranu disleksiju. Rezultati su pokazali poboljšanje od 24 % na standardiziranim testovima razumijevanja. Autori također izvještavaju da je najveće poboljšanje zabilježeno upravo kod djece s najlošijim vještinama čitanja (njih devet od 20). Konačno, mjerenje pokreta oka u kombinaciji s virtualnom stvarnošću također je našlo primjenu u terapiji disleksije (Saunier i sur., 2022). Autori u radu predstavljaju rješenje koje služi praćenju i procjeni uspješnosti terapije, a temelji se na videoigri integriranoj s mjerenjem pokreta oka i sučeljem mozga i računala (engl. *brain-computer interface, BCI*). Kao prednost takvog rješenja ističe se povećana motiviranost djece da sudjeluju u takvom obliku terapije – prema riječima autora, terapija se pretvara u veliku avanturu - i mogućnost da ta tehnologija služi i roditeljima da prate napredak svoje djece. Kao ozbiljno ograničenje studije sami autori navode nedostatak kliničkih studija uspješnosti. Drugim riječima, glavni doprinos rada sastoji se u prijedlogu tehnološkog rješenja, tj. integraciji virtualne stvarnosti, videoigara, mjerenja pokreta oka i sučelja mozga i računala. To rješenje zahtijeva integraciju svih sustava u uređaj koji se stavlja na glavu, s tim da ne bude težak i nespretan djetetu.

Čak i kad fokus istraživanja nije na upotrebi mjerenja pokreta oka u terapiji, istraživanja ističu njezinu korist u individualiziranoj intervenciji, tj. pristupu osobi s disleksijom s obzirom na njezine kognitivne vještine i strategije (Rayner i sur., 2003). Autori istražuju kontrolu pokreta oka na tekstu u kojem riječi (kontrolirane s obzirom na njihovu čestotnost) nestaju 60 milisekundi nakon što su fokusirane (engl. *gaze-contingency paradigm*). Dulje vrijeme fiksacija zabilježeno je za riječi niske čestotnosti, što je konzistentno s modelima kognitivne kontrole pokreta oka, tj. idejom da jezična obrada (jezično razumijevanje) kontrolira pokrete oka i da promjene u putanji pogleda kod osoba s disleksijom, što se redovito izvještava u studijama disleksije, nisu posljedica okulomotornog, nego deficita na kognitivnoj razini (tj. na razini jezične obrade).

Finally, eye-tracking combined with virtual reality has also been applied in dyslexia therapy (Saunier et al., 2022). The authors present a solution for monitoring and assessing therapy effectiveness, integrating a video game with eye-tracker and a brain-computer interface (BCI). The main advantage of this approach is the increased motivation of children to participate - according to the authors, the therapy turns into an adventure - and the ability for parents to track their child's progress. However, a significant limitation of the study is the lack of clinical trials evaluating its effectiveness. In other words, the main contribution of the study is the proposal of a technological solution integrating virtual reality, video games, eye-tracking, and BCI. This solution requires integrating all systems into a head-mounted device that remains lightweight and comfortable for children.

Even when the focus of research is not on using an eye-tracker in therapy, studies highlight its usefulness in individualised interventions, i.e., tailoring approaches to individuals with dyslexia based on their cognitive skills and strategies (Rayner et al., 2003). The authors examined eye movement control in a text where words (controlled for frequency) disappeared 60 milliseconds after being fixated (a gaze-contingency paradigm). Longer fixation times were recorded for low-frequency words, consistent with cognitive control models of eye movement, suggesting that language processing (comprehension) governs eye movements. This supports the idea that changes in gaze patterns observed in dyslexia studies are due to cognitive deficits rather than oculomotor deficits.

Eye movement measurement is also used to study optimal text presentation for individuals with dyslexia. It is well known that some fonts are easier to read than others for people with dyslexia, and the development of dyslexia-friendly fonts is an active area of research, sometimes yielding conflicting results. Eye-tracking should provide an objective measure of font suitability for individuals with dyslexia by analysing gaze patterns. The first study with this aim was conducted by Rello and Baeza-Yates in 2016, in which individuals with dyslexia (aged 11-50 years) read twelve different texts written in different fonts. Fixation

Metoda mjerenja pokreta oka također se upotrebljava u istraživanjima optimalnog prikaza teksta osobama s disleksijom. Poznato je da su neki fontovi lakši, a neki teži za čitati osobama s disleksijom i razvoj fontova za disleksiju živo je područje istraživanja s katkada oprečnim rezultatima. Metoda mjerenja pokreta oka trebala bi putem analize putanje pogleda dati objektivnu mjeru prilagođenosti nekog fonta osobama s disleksijom. Prva je studija s takvim ciljem Rello i Baeza-Yates, (2016), u kojoj su autori osobama s disleksijom (11-50 godina starosti) dali dvanaest različitih tekstova napisanih različitim fontovima. Analiziralo se vrijeme fiksacija na pojedine dijelove teksta, razumijevanje teksta i preferencije sudionika. Iznenađujuće, fontovi posebno napravljeni za osobe s disleksijom nisu doprinijeli boljem čitanju i razumijevanju u odnosu na Verdanu ili Helveticu. Osim njih, autori predlažu upotrebu Ariala pa čak i Couriera s obzirom na to da se radi o *monotype* fontu, tj. fontu u kojem svako slovo zauzima jednako mjesta, što odgovara osobama s disleksijom. Nakošen font pokazao se kao onaj koji treba izbjegavati u tekstovima namijenjenima osobama s disleksijom.

Suprotnim putem krenuli su Stark i sur., (2022) nastojeći konstruirati font koji otežava čitanje kako bi predočili teškoće s kojima se susreću osobe s disleksijom dok čitaju. Font jednostavno briše oko 40 % svakog slova što usporava čitanja, smanjuje razumljivost i izaziva frustraciju kod čitatelja. Nije samo odabir fonta važan; važna je i veličina fonta i razmak između slova (Masulli i sur., 2018). Polazeći od ideje da djeca s disleksijom često pokazuju manji raspon vizualne pažnje i da imaju problema s gomilanjem slova, tj. interferencijom susjednih slova, autori su povećali razmak između slova i dobili kraće fiksacije i dulje sakade i kod djece s disleksijom i u skupini djece tipičnog razvoja čitanja, s tim da je nađena zanimljiva interakcija, tj. povećanje razmaka među slovima više je skratilo vrijeme fiksacija kod djece s disleksijom. Ta činjenica da je tekst s većim razmakom među slovima lakši osobama s disleksijom, tj. da više utječe na putanju pogleda osoba s disleksijom nastojala se iskoristiti i za otkrivanje disleksije pomoću algoritma strojnog učenja (Szalma i sur., 2021). Najviša točnost u klasifikaciji (više od 73 %) postignuta je s povećanim razmakom, dok je najniža točnost bila pri najmatimes on text segments, comprehension, and participant preferences were analysed. Surprisingly, fonts specifically designed for dyslexia did not improve reading or comprehension compared to Verdana or Helvetica. The authors also suggested using Arial, and even Courier, a monospaced font where each letter takes up the same space, which benefits individuals with dyslexia. Italicised fonts were identified as ones to avoid in texts intended for dyslexic readers.

Stark et al. (2022) took the opposite approach, designing a font that hinders reading to simulate the difficulties faced by individuals with dyslexia. This font erases about 40% of each letter, slowing reading, reducing comprehension, and causing frustration. However, font choice is not the only factor - font size and letter spacing are also important (Masulli et al., 2018). Based on the idea that children with dyslexia often have a narrower visual attention span and struggle with letter crowding (interference from adjacent letters), the authors increased letter spacing, resulting in shorter fixations and longer saccades in both children with dyslexia and typically developing readers. Interestingly, the increased spacing had a greater effect on reducing fixation times for children with dyslexia. This effect has also been explored for dyslexia detection using machine learning algorithms (Szalma et al., 2021). The highest classification accuracy (over 73%) was achieved with increased letter spacing, while the lowest accuracy was associated with the smallest spacing. However, these differences were not statistically significant.

Letter spacing is studied not only for its practical implications, but also for its theoretical significance: the facilitating effect of increased spacing in text for dyslexic readers is attributed to reduced inhibition of parafoveal stimuli, suggesting a link between dyslexia and attention disorders. However, these results are not conclusive. A study manipulating spacing and stimulus positioning in the left and right visual fields, involving children with dyslexia, an age-matched control group, and a reading skill-matched control group (Bellocchi et al., 2019), reported a significant interaction between visual field and spacing. Specifically, the njem razmaku. Ipak, te se razlike nisu pokazale statistički značajnima. Utjecaj razmaka na čitanje proučava se zato što ima teorijski značaj; facilitirajući učinak razmaka kod osoba s disleksijom tumači se manjom potrebom za inhibicijom parafovealnih podražaja, što bi impliciralo povezanost disleksije i poremećaja pažnje. Ipak, rezultati nisu jednoznačni. U studiji u kojoj su manipulirani razmaci, ali i položaj podražaja u lijevom i desnom vidnom polju, a uključena djeca s disleksijom, kontrolna skupina prema dobi i druga kontrolna skupina prema vještini čitanja (Bellocchi i sur., 2019), dobivena je značajna interakcija između vizualnog polja i razmaka, tj. pogled na riječ nakon prikazivanja na zaslonu pao je dalje od „preferiranog položaja“ (malo lijevo od sredine riječi) više ako bi podražaj bio prikazan u lijevom vidnom polju, nego desno i više za riječi s većim razmakom među slovima. Također, kontrolna skupina po dobi općenito je fiksirala bliže preferiranom položaju, naročito u normalnom razmaku među slovima. Ustvari, sve tri skupine djece teško su se nosile s povećanim razmakom. Studija je kao kategoriju važnu za razvoj vještina čitanja istaknula razvoj strategije ciljanja preferiranog položaja pogleda unutar riječi, i to u sakadama slijeva nadesno. Povećan razmak nije se pokazao kao facilitirajući čimbenik u planiranju sakada, ali je imao pozitivan učinak u smanjenju vizualnog gomilanja (engl. *visual crowding*).

Iako u pretraženim bazama još nema studija koje upotrebljavaju font koji olakšava osobama s disleksijom čitanje hrvatskih tekstova, Omotype (https://omotype.com/), taj font omogućuje sve spomenute manipulacije fontom, od veličine do razmaka među slovima, ovaj font omogućuje dodatno razlikovanje onih slova koja su simetrična (d, b). Facilitirajući efekt takvog fonta, ipak, valjalo bi istražiti.

Na kraju, ne utječu samo slova, fontovi i razmaci na olakšavanje čitanja u osoba s disleksijom. Rello i Bigham (2017) izvještavaju o bojama pozadine koje utječu na čitljivost teksta. Tople boje (narančasta, žuta) povoljno utječu na čitanje, dok siva, plava i zelena smanjuju čitljivost teksta osobama s disleksijom. Utjecaj boje pozadine ili primijenjenog filtera u boji na čitljivost može se objasniti Meares-Irlenovim sindromom (MIS) koji je povezan s disleksijom (Irlen, 1997; Kriss, Evans, 2005), tj. često se dija-

gaze on a word after stimulus presentation deviated more from the “preferred position” (slightly left of centre) when the stimulus was in the left visual field rather than the right. The deviation was more for words with increased spacing as well. Additionally, the age-matched control group fixated closer to the preferred position, especially with normal letter spacing. In fact, all three groups struggled with increased spacing. The study highlighted the development of a preferred gaze position within words as an important factor in reading skill development, particularly in left-to-right saccades. While increased spacing did not facilitate saccade planning, it did help reduce visual crowding.

Although there are no studies that have used a dyslexia-friendly font for Croatian texts, Omotype (https://omotype.com/) allows for the above-mentioned font manipulations, including size and letter spacing. This font also differentiates between symmetrical letters (e.g., d and b), which may be beneficial for dyslexic readers. However, the ways in which it facilitate reading still needs to be investigated.

Finally, it is not only letters, fonts, and spacing that influence reading facilitation in people with dyslexia. Rello and Bigham (2017) reported that background colours also influence the legibility of text. Warm colours (orange, yellow) have a positive effect on reading, while grey, blue, and green reduce the readability of text for people with dyslexia. The effect of background colours or colour filters on readability can be explained by the Meares-Irlen syndrome (MIS), which is often observed in people with dyslexia (Irlen, 1997; Kriss & Evans, 2005). This syndrome is characterised by “visual stress”, which leads to distortions in visual perception and makes it difficult for those affected to follow lines of text, since they see that the letters appear to overlap. The use of coloured lenses alleviates the difficulties associated with MIS. The colours are prescribed individually (as tinted lenses) with a high degree of precision. However, the results are not consistent.

Ritchie et al. (2011) reported that they found no effect of coloured lenses on reading in children with reading difficulties. The study included gnosticira kod osoba s disleksijom. Radi se o „vizualnom stresu“ koji dovodi do iskrivljavanja vizualne percepcije, pa osoba teško slijedi liniju teksta ili ima osjećaj da joj se slova preklapaju. Upotreba filtera u boji olakšava teškoće povezane s MIS-om, a boje se poput lijekova propisuju individualno (kao obojene leće), pri čemu je potrebna znatna razina preciznosti. Rezultati ipak nisu jedinstveni. Ritchie i sur. (2011) izvještavaju da nisu našli efekt filtera u boji na čitanje kod djece s poteškoćama u čitanju. Istraživanje je osim uvjeta bez filtera uključivalo uvjet s propisanom i nepropisanom bojom za sudionike, pa se negativan rezultat ne može pripisati slaboj preciznosti eksperimenta. Efekt filtera u boji na čitanje istraživao se i bez mjerenja pokreta oka, mjerenjem vremena čitanja i praćenja putanje miša (osobe s disleksijom i s MSI mišem prevale veću udaljenost u čitanju, Kriss, Evans, 2005). Neke studije koje uključuju mjerenje pokreta oka potvrdila su povoljan utjecaj odabira odgovarajuće boje pozadine na čitanje; već označavanje teksta bojom (eng. *highlighting*) pokazalo je pozitivan učinak na čitanje kod djece s disleksijom (Ikeshita-Yamazoe i sur. 2015). Druge, pak, ne nalaze efekt filtera u boji, tj. obojeni filteri ne utječu na tečnost u čitanju, ali ih sudionici preferiraju (Denton, Meindl, 2016). Budući da preferencije ne koreliraju s uspješnošću, autori predlažu oprez i potrebu za empirijski validiranim intervencijama.

ZAKLJUČAK

Kao što je spomenuto u Uvodu, metoda mjerenja pokreta oka našla je primjenu u svim vidovima proučavanja disleksije, od teorija o uzrocima disleksije do terapije i asistivne tehnologije. Budući da se radi o eksperimentalnoj metodi, razumljivo je da se najveći broj studija bavi teorijskim pitanjima eksperimentalno dokazujući ili opovrgavajući pojedine hipoteze. Teorija fonološkog deficita kao i teorija okulomotornog deficita najzastupljenije su teorije u tim studijama, što je razumljivo s obzirom na narav zadataka i narav same metode. Razvojem umjetne inteligencije i algoritama strojnog učenja u novije se vrijeme metoda mjerenja pokreta oka sve više upotrebljava u dijagnostičke svrhe iskorištavajući snagu tih algoritama u klasifikaciji signala. Istovremeno,

conditions with and without filters, as well as individually prescribed and non-prescribed colours for participants, so the negative result cannot be attributed to a lack of experimental precision. The effect of colour filters on reading was investigated without measuring eye movements as well. Instead, reading time and mouse tracking were used to test the effects of using colour filters (people with dyslexia and MIS cover a greater distance with the mouse when reading, Kriss & Evans, 2005).

Some studies that incorporate eye-tracking have confirmed the positive effects of selecting an appropriate background colour on reading in children with dyslexia. In fact, highlighting the text also showed a positive effect on reading in children with dyslexia (Ikeshita-Yamazoe et al., 2015). However, other studies have found no effect of coloured filters, i.e., tinted filters had no effect on reading fluency, even though participants preferred them (Denton & Meindl, 2016). Since preferences do not correlate with objective measures, the authors advise caution and emphasise the need for empirically validated interventions.

CONCLUSION

As mentioned in the introduction, the eye-tracking method has been applied in all aspects of dyslexia research, from theories about its causes to therapy and assistive technology. As an experimental method, it is predominantly used for theoretical research, and testing or refuting various hypotheses. The phonological deficit theory and the oculomotor deficit theory are the most widely studied, given the nature of the tasks and the method itself.

With the development of artificial intelligence and machine learning algorithms, eye-tracking has recently been increasingly used for diagnostic purposes, leveraging the power of these algorithms in signal classification. At the same time, research is becoming more computational in nature, while focusing less on psychological, linguistic, or speech and language pathology details. The future development of this method will undoubtedly move towards mass adoption and ease of use. One radovi su sve više računalne naravi, a sve manje se bave psihološkim, lingvističkim ili logopedskim detaljima. Budući razvoj metode sigurno će ići prema masovnosti i jednostavnosti upotrebe. Razlog nije samo opća informatizacija i automatizacija ljudskih poslova. Procjena smjera pogleda biološki je usađena u ljudima – prema hipotezi kooperativnog oka vidljiva bjeloočnica evoluirala je kako bi se olakšala kooperacija među ljudima (iako možda zapovijed generala Putnama u bitci za Bunker Hill, 1775.: „Ne pucajte dok ne vidite bijelo u njihovim očima!" sugerira suprotno). Primjena preciznijih algoritama za detekciju smjera pogleda na web-kamerama, tabletima i pametnim telefonima, što je neizbježna budućnost, sigurno će doprinijeti široj upotrebi mjerenja pokreta oka u logopediji.

reason for this is the contemporary general informatisation and automation of human tasks. The ability to assess gaze direction is biologically ingrained in humans - according to the cooperative eye hypothesis, the visible sclera evolved to facilitate cooperation among people (although general Putnam's command at the Battle of Bunker Hill in 1775, "Don't fire till you see the whites of their eyes!" might suggest otherwise). The application of more precise gaze detection algorithms in webcams, tablets, and smartphones, which is inevitable in the future, will undoubtedly contribute to the broader use of eye movement measurement in speech therapy. In any case, the use of colour filters is based on the magnocellular theory of dyslexia (Aleci, 2014), but inconsistent results indicate the need for further research in this area.

REFERENCES

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (5th ed.)*. American Psychiatric Publishing, Washington DC.

Araújo, S., & Faísca, L. (2019). A Meta-Analytic Review of Naming-Speed Deficits in Developmental Dyslexia. *Scientific Studies of Reading*, *23*(5), 349–368. https://doi.org/10.1080/10888438.2019.1572758

Araújo, S., Huettig, F., & Meyer, A. S. (2020). What Underlies the Deficit in Rapid Automatized Naming (RAN) in Adults with Dyslexia? Evidence from Eye Movements. *Scientific Studies of Reading*, *25*(6), 534–549. https://doi.org/10.1080/10888438.2020.1867863

Stéphanie Bellocchi, Massendari, D., Grainger, J., & Stéphanie Ducrot. (2018). *Effects of inter-character spacing on saccade programming in beginning readers and dyslexics. 25*(4), 482–506. https://doi.org/10.1080/09297049.2018.1504907

Black, J. L., Collins, D. W. K., De Roach, J. N., & Zubrick, S. (1984). A Detailed Study of Sequential Saccadic Eye Movements for Normal- and Poor-Reading Children. *Perceptual and Motor Skills*, *59*(2), 423–434. https://doi.org/10.2466/pms.1984.59.2.423

Blythe, H. I., Dickins, J. H., Kennedy, C., & Liversedge, S. P. (2020). The role of phonology in lexical access in teenagers with a history of dyslexia. *Plos One*, 15(3), e0229934. https://doi.org/10.1371/journal.pone.0229934

Bradley, L., & Bryant, P. (1978). Difficulties in auditory organisation as a possible cause of reading backwardness. *Nature* 271, 746–747. https://doi.org/10.1038/271746a0

Bucci, M. P., Carzola, B., Fiucci, G., Potente, C., & Caruso, L. (2018). Computer Based Oculomotor Training Improves Reading Abilities in Dyslexic Children: Results from A Pilot Study. *Sports Injury and Medicine* (JSIMD-130), 2018(1). https://doi.org/10.29011/JSIMD-130

Denton, T. F., Meindl, J. N. (2016). The Effect of Colored Overlays on Reading Fluency in Individuals with Dyslexia. *Behavior Analysis in Practice*, *9*(3), 191–198. https://doi.org/10.1007/S40617-015-0079-7

Desroches, A., Joanisse, M. F., & Robertson, E. K. (2006). Specific phonological impairments in dyslexia revealed by eyetracking. *Cognition*, 100, B32-B42. https://doi.org/10.1016/j.cognition.2005.09.001

Eden, G. F., Stein, H. M., Wood, F. B., & Wood, F. B. (1993). Differences in Eye Movements and Reading Problems In Dyslectic and Normal Children. *Vision Research*, 34(10), 1345-58. https://doi.org/10.1016/0042-6989(94)90209-7

Franzen, L., Stark, Z., Johnson, A.P. (2021). Individuals with dyslexia use a different visual sampling strategy to read text. *Scientific Report,* 11, 6449. https://doi.org/10.1038/s41598-021-84945-9

Frith, U. (1999). Paradoxes in the definition of dyslexia. *Dyslexia: An International Journal of Research and Practice, 5*(4), 192–214. https://doi.org/10.1002/(SICI)1099-0909(199912)5:4<192::AID-DYS144>3.0.CO;2-N

Gordon, P. C., Hoedemaker, R. S. (2016). Effective scheduling of looking and talking during rapid automatized naming. *Journal of Experimental Psychology. Human Perception and Performance*, *42*(5), 742–760. https://doi.org/10.1037/ xhp0000171

Huang, X., Jing, J., Zou, X.-B., Wang, M.-L., Li, X.-H., Lin, A.-H. (2008). Eye movements characteristics of Chinese dyslexic children in picture searching. *Chinese Medical Journal*, *121*(17), 1617-1621.

Huettig, F. and Brouwer, S. (2015). Delayed anticipatory spoken language processing in adults with dyslexia—evidence from eye-tracking. *Dyslexia*, *21*(2), 97-122. https://doi.org/10.1002/dys.1497

Hutzler, F., Kronbichler, M., Jacobs, A.M., Wimmer, H. (2006). Perhaps correlational but not causal: no effect of dyslexic readers' magnocellular system on their eye movements during reading. *Neuropsychologia*, *44*(4), 637-48. https://doi.org/10.1016/j.neuropsychologia.2005.06.00

Ikeshita-Yamazoe, H., Yamaguchi, S., Morioka, T., Yamazoe, T. (2015). The Influence of Visual Information During Reading in Children with Dyslexia. *IAFOR,* http://papers.iafor.org/wp-content/uploads/papers/acset2015/ACSET2015_20150.pdf

Iles J., Walsh V., Richardson A. (2000). Visual search performance in dyslexia. *Dyslexia*, 6(3):163-77. https://doi.org/10.1002/1099-0909(200007/09)6:3<163::AID-DYS150>3.0.CO;2-U

Irlen, H. (1997). Reading problems and Irlen Coloured Lenses. *Dyslexia Review*, Summer, 4–7.

Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology*, *8*(4), 441–480. https://doi.org/10.1016/0010-0285(76)90015-3

Kasper, D. L., Braunwald, E., Fauci, A. S., Hauser, S. L., Longo, D. L., Jameson, J. L. (2005). *Harrison's Principles of Internal Medicine.* New York, McGraw-Hill.

Kasprowski, P., & Harezlak, K. (2017). Gaze Self-Similarity Plot - A New Visualization Technique. *Journal of Eye Movement Research*, *10*(5). https://doi.org/10.16910/jemr.10.5.3

Kasprowski, P. (2024). Utilizing Gaze Self Similarity Plots to Recognize Dyslexia when Reading. *Proceedings of the 2024 Symposium on Eye Tracking Research and Applications*, 1–5. https://doi.org/10.1145/3649902.3656494

Kriss, I., & Evans, B. J. (2005). The relationship between dyslexia and Meares-Irlen Syndrome. *Journal of Research in Reading*, *28*(3), 350-364. https://doi.org/10.1111/j.1467-9817.2005.00274.x

Kutlu, E., Klein-Packard, J., Jeppsen, C., Tomblin, J. B., & McMurray, B. (2024). The development of real-time spoken and written word recognition derives from changes in ability, not maturation, *Cognition, 251*, 105899. https://doi.org/10.1016/j.cognition.2024.105899

Lohvansuu, K., Torppa, M., Ahonen, T., Eklund, K., Hämäläinen, J. A., Leppänen, P. H. T., & Lyytinen, H. (2021). Unveiling the Mysteries of Dyslexia—Lessons Learned from the Prospective Jyväskylä Longitudinal Study of Dyslexia. *Brain Sciences*, *11*(4), 427. https://doi.org/10.3390/brainsci11040427

Luke, S. G., Tolley, C., Gutierrez, A., Smith, C., Brown, T., Woodruff, K., & Ford, O. (2024). The perceptual span in dyslexic reading and visual search. *Dyslexia*, *30*(4). https://doi.org/10.1002/dys.1783

Masulli, F., Galluccio, M., Gerard, C. L., Peyre, H., Rovetta, S., & Bucci, M. P. (2018). Effect of different font sizes and of spaces between words on eye movement performance: An eye tracker study in dyslexic and non-dyslexic children. *Vision research*, *153*, 24-29. https://doi.org/10.1016/j.visres.2018.09.008

Morgan, W. P. (1896). A Case of Congenital Word Blindness. *BMJ*, *2*(1871), 1378–1378. https://doi.org/10.1136/bmj.2.1871.1378

Nilsson Benfatto M., Öqvist Seimyr G., Ygge J., Pansell T., Rydberg A., & Jacobson C. (2016). Screening for Dyslexia Using Eye Tracking during Reading. *PLoS ONE* 11(12): e0165508. https://doi.org/10.1371/journal.pone.0165508

Nerušil, B., Polec, J., Škunda, J., Kačur, J. (2021). Eye tracking based dyslexia detection using a holistic approach. *Scientific Reports*, 11(1), 15687. https://doi.org/10.1038/s41598-021-95275-1

Orton, S. T. (1925). Word-blindness in school children. *Archives of Neurology & Psychiatry*, *14*(5), 581-615. https://doi.org/10.1001/archneurpsyc.1925.02200170002001

Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D. et al. (2021). PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. BMJ 372(160), 1-36. https://doi.org/10.1136/bmj.n160

Pavlidis, G. T. (1981). Do eye movements hold the key to dyslexia. *Neuropsychologia*, 19(1), 57-64. https://doi.org/10.1016/0028-3932(81)90044-0

Pennington, B. F., Santerre-Lemmon, L., Rosenberg, J., MacDonald, B., Boada, R., Friend, A., Leopold, D., Samuelsson, S., Byrne, B., Willcutt, E.G., & Olson, R. K. (2012). Individual prediction of dyslexia by single versus multiple deficit models. *Journal of abnormal psychology*, 121(1), 212-224. https://doi.org/10.1037/a0025823

Pensiero, S., Accardo, A., Michieletto, P., & Brambilla, P. (2013). Saccadic alterations in severe developmental dyslexia. *Case Reports in Neurological Medicine*, 2013(1), 406861. https://doi.org/10.1155/2013/406861

Perera, P., Harshani, H., Shiratuddin, M. F., Wong, K. W., & Fullarton, K. (2018). EEG signal analysis of writing and typing between adults with dyslexia and normal controls. *International Journal of Interactive Multimedia and Artificial Intelligence*, *5*(1), 62-67. https://doi.org/10.9781/ijimai.2018.04.005

Peterson, R. L., & Pennington, B.F. (2012). Developmental dyslexia. *Lancet*, *26*(379), 1997-2007. https://doi.org/10.1016/S0140-6736(12)60198-6

Ramus, F., Pidgeon, E., & Frith, U. (2003). The relationship between motor control and phonology in dyslexic children. *Journal of Child Psychology and Psychiatry*, *44*(5), 712–722. https://doi.org/10.1111/1469-7610.00157

Ramus, F., & Ahissar, M. (2012). Developmental dyslexia: The difficulties of interpreting poor performance, and the importance of normal performance. Cognitive *Neuropsychology*, 29(1–2), 104–122. https://doi.org/10.1080/02643294.2012.677420

Ramus, F. (2014). Neuroimaging sheds new light on the phonological deficit in dyslexia. *Trends in Cognitive Sciences*, *18*(6), 274–275. https://doi.org/10.1016/j.tics.2014.01.009

Rayner, K., Liversedge, S. P., White, S. J., & Vergilino-Perez, D. (2003). Reading Disappearing Text. *Psychological Science*, *14*(4), 385–388. https://doi.org/10.1111/1467-9280.24483

Rayner, K., Murphy, L. A., Henderson, J. M., & Pollatsek, A. (1989). Selective attentional dyslexia. *CognitiveNeuropsychology*, *6*(4),357–378. https://doi.org/10.1080/02643298908253288

Rello, L., & Baeza-Yates, R. (2016). The Effect of Font Type on Screen Readability by People with Dyslexia. *ACM Transactions on Accessible Computing*, *8*(4), 1–33. https://doi.org/10.1145/2897736

Rello, L., & Ballesteros, M. (2015). Detecting readers with dyslexia using machine learning with eye tracking measures. *Proceedings of the 12th International Web for All Conference*. https://doi.org/10.1145/2745555.2746644

Rello, L., Bigham, J. P. (2017). Good Background Colors for Readers: A Study of People with and without Dyslexia. *Conference on Computers and Accessibility*, 72–80. https://doi.org/10.1145/3132525.3132546

Rello, L., Romero, E., Rauschenberger, M., Ali, A., Williams, K., Bigham, J. P., & White, N. C. (2018). Screening Dyslexia for English Using HCI Measures and Machine Learning. *Proceedings of the 2018 International Conference on Digital Health*. https://doi.org/10.1145/3194658.3194675

Ritchie, S. J., Della Sala, S., & McIntosh, R. D. (2011). Irlen Colored Overlays Do not Alleviate Reading Difficulties. *Pediatrics*, *128*(4), e932-e938. https://doi.org/10.1542/peds.2011-0314

Saunier, L., Panouilleres, M., Fetita, C., & Preda, M. (2022, November 2). *Visual Rehabilitation for Learning Disorders in Virtual Reality: Visual Rehabilitation for Learning Disorder in VR*. ACM Digital Library; Association for Computing Machinery. https://doi.org/10.1145/3564533.3564574

Schiavo, G., Mana, N., Mich, O., Zancanaro, M., Zancanaro, M., & Job, R. (2021). Attention-driven read-aloud technology increases reading comprehension in children with reading disabilities. *arXiv: Human-Computer Interaction*. https://doi.org/10.1111/JCAL.12530

Stark, Z., Franzen, L., & Johnson, A. P. (2021). Insights from a dyslexia simulation font: Can we simulate reading struggles of individuals with dyslexia? *Dyslexia*. https://doi.org/10.1002/dys.1704

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia*, *7*(1), 12–36. https://doi.org/10.1002/dys.186

Stella M, & Engelhardt PE. (2019). Syntactic ambiguity resolution in dyslexia: An examination of cognitive factors underlying eye movement differences and comprehension failures. *Dyslexia*, *25*, 115–141. https://doi.org/10.1002/dys.1613

Swan, D., & Goswami, U. (1997). Phonological awareness deficits in developmental dyslexia and the phonological representations hypothesis. *Journal of Experimental Child Psychology*, *66*(1), 18–41. https://doi.org/10.1006/jecp.1997.2375

Szalma, J., Amora, K. K., Vidnyánszky, Z., & Weiss, B. (2021). Investigating the Effect of Inter-letter Spacing Modulation on Data-Driven Detection of Developmental Dyslexia Based on Eye-Movement Correlates of Reading: A Machine Learning Approach. In *Pattern Recognition. ICPR International Workshops and Challenges: Virtual Event, January 10–15, 2021, Proceedings, Part III*, pp. 467-481. Springer International Publishing.

Tanenhaus, M. K., Magnuson, J. S., Dahan, D., & Chambers, C. (2000). Eye movements and lexical access in spoken-language comprehension: evaluating a linking hypothesis between fixations and linguistic processing. *Journal of Psycholinguistic Research*, *29*(6), 557–580. https://doi.org/10.1023/a:1026464108329

Tiadi, A., Gérard, C. L., Peyre, H., Bui-Quoc, E., & Bucci, M. P. (2016). Immaturity of visual fixations in dyslexic children. *Frontiers in human neuroscience*, *10*, 58. https://doi.org/10.3389/fnhum.2016.00058

Trauzettel-Klosinski, S., MacKeben, M., Reinhard, J., Feucht, A., Dürrwächter, U., Klosinski, G. (2002). Pictogram naming in dyslexic and normal children assessed by SLO. *Vision Research*, 42(6), 789-799. https://doi.org/10.1016/S0042-6989(01)00318-2.

Vajs, I., Kovic, V., Papic, T., Savic, A. M., & Jankovic, M. M. (2022). Dyslexia detection in children using eye tracking data based on VGG16 network. *2022 30th European Signal Processing Conference (EUSIPCO)*. https://doi.org/10.23919/eusipco55093.2022.9909817

Wright C. M., Conlon E. G., & Dyck M. (2012). Visual search deficits are independent of magnocellular deficits in dyslexia. *Ann Dyslexia*, 62(1), 53-69. https://doi.org/10.1007/s11881-011-0061-1

Zoccolotti, P. (2022). Success Is Not the Entire Story for a Scientific Theory: The Case of the Phonological Deficit Theory of Dyslexia. *Brain Sciences*, *12*(4), 425. https://doi.org/10.3390/brainsci12040425