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Rethinking the neural noise hypothesis of dyslexia: from multisensory integration to excitation/inhibition imbalance

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ABSTRACT

Dyslexia is a specific learning disorder characterized by reduced reading fluency, accuracy, and comprehension. It affects approximately 7-12% of the population and is more commonly diagnosed in males than females. While several cognitive and neural factors associated with dyslexia have been identified, the precise causal mechanisms underlying reading difficulties remain unclear. Since reading acquisition relies on integrating auditory and visual stimuli, deficits in low-level multisensory integration may also contribute to dyslexia. Some studies have reported such deficits, but effect sizes varied depending on whether participants were matched for sex. Despite the higher prevalence of dyslexia in males and emerging evidence of sex-based differences in its neural underpinnings, no previous studies have specifically examined sex differences in multisensory integration. Thus, the first aim of this thesis was to address this gap by directly assessing sex-specific effects in low-level multisensory integration in dyslexia.

One of the latest causal theories of dyslexia, the neural noise hypothesis, proposes that reading difficulties stem from increased cortical excitability, leading to cognitive impairments in phonological awareness, rapid automatized naming, and multisensory integration in dyslexia. Non-invasive estimates of excitatory/inhibitory (E/I) balance in the brain can be obtained through various electroencephalography (EEG) power spectrum measures, including aperiodic (exponent, offset) and periodic (beta and gamma power) components. To date, no study has tested the neural noise hypothesis of dyslexia by examining EEG E/I balance biomarkers in relation to proposed cognitive deficits. Thus, the second aim of this thesis was to investigate these relationships.

Regarding the first aim, a study of 88 adolescents and young adults revealed that only males with dyslexia exhibited deficits in multisensory integration of simple, non-linguistic stimuli, as assessed by a simple reaction time task. At the neural level, both males and females with dyslexia showed smaller differences in responses between multisensory and unisensory conditions in the N1 and N2 components (event-related potentials related to sensory processing) compared to controls. However, in a subsample of 80 participants matched for non-verbal IQ, only males with dyslexia exhibited a smaller difference in neural responses to multisensory versus unisensory conditions in the N1 component of the left hemisphere. These findings provide novel insights into sex-specific cognitive processes related to reading difficulties.

Regarding the second aim, results from a sample of 120 participants, analyzed using Bayesian statistics, revealed no evidence of group differences in any EEG E/I balance biomarkers (exponent, offset, beta power) at rest or during a spoken language task. However, a positive indirect relationship between beta power, phonological awareness, and reading speed was found. These findings do not support the prediction that cortical hyperexcitability underlies dyslexia, underscoring the need to explore alternative neural mechanisms associated with reading difficulties. Furthermore, the observed sex-specific effects in multisensory integration highlight the potential for distinct cognitive and neural pathways in males and females with dyslexia, which should be considered in future research frameworks.

STRESZCZENIE

Dysleksja jest specyficznym zaburzeniem uczenia się, charakteryzującym się obniżoną płynnością, dokładnością i rozumieniem w czytaniu. Dotyka około 7-12% populacji i jest częściej diagnozowana u mężczyzn niż u kobiet. Chociaż niektóre mechanizmy poznawcze i neuronalne związane z dysleksją zostały zidentyfikowane, to dokładne relacje przyczynowe leżące u podstaw trudności w czytaniu wciąż pozostają niejasne. Z uwagi na to, że nabywanie umiejętności czytania opiera się na integracji bodźców słuchowych i wzrokowych, deficyty w integracji multisensorycznej prostych bodźców również mogą przyczyniać się do powstawania dysleksji. Chociaż niektóre wcześniejsze badania wykazały takie deficyty, ich wielkość efektu różniła się w zależności od tego, czy uczestnicy byli dopasowani pod względem płci. Pomimo częstszego występowania dysleksji u mężczyzn i pojawiających się dowodów wskazujących na różnice płciowe w jej neuronalnych korelatach, dotychczas w żadnym badaniu nie analizowano potencjalnych różnic międzypłciowych w integracji multisensorycznej. Z tego względu, pierwszym celem niniejszej pracy było wypełnienie tej luki poprzez bezpośrednią ocenę różnic płciowych w integracji multisensorycznej prostych bodźców wzrokowych i słuchowych w dysleksji.

Jedna z najnowszych teorii dysleksji, hipoteza „szumu neuronalnego", zakłada, że trudności w czytaniu wynikają ze zwiększonej pobudliwości korowej, która na poziomie poznawczym prowadzi do zaburzeń w zakresie świadomości fonologicznej, szybkiego nazywania oraz integracji multisensorycznej u osób z dysleksją. Nieinwazyjnej oceny stosunku aktywności pobudzającej do hamującej w mózgu można dokonać za pomocą różnych miar z widma mocy sygnału elektroencefalograficznego (EEG), w tym z sygnału aperiodycznego (nachylenie widma) oraz periodycznego (moc w pasmach beta i gamma). Do tej pory jednak, żadne badanie nie zweryfikowało hipotezy szumu neuronalnego w dysleksji przy użyciu biomarkerów z sygnału EEG w odniesieniu do proponowanych deficytów poznawczych. Stąd, drugim celem niniejszej pracy było zbadanie tych zależności.

W odniesieniu do pierwszego celu pracy przeprowadzono badanie obejmujące 88 nastolatków i młodych dorosłych. Wykazało ono, że deficyty w integracji multisensorycznej prostych, niejęzykowych bodźców w zadaniu mierzącym czasy reakcji, występowały wyłącznie u mężczyzn z dysleksją. Na poziomie neuronalnym, zarówno mężczyźni, jak i kobiety z dysleksją wykazywali mniejsze różnice w odpowiedziach między warunkami multisensorycznymi i unisensorycznymi w komponentach N1 i N2 (potencjały wywołane związane z przetwarzaniem bodźców zmysłowych) w porównaniu z grupą kontrolną. Z kolei w podgrupie 80 uczestników dopasowanych pod względem ilorazu inteligencji niewerbalnej, jedynie mężczyźni z dysleksją wykazywali mniejszą różnicę w odpowiedziach neuronalnych na bodźce multisensoryczne i unisensoryczne w komponencie N1 w lewej półkuli. Wyniki te dostarczają nowych danych na specyficzne dla płci procesy poznawcze związane z trudnościami w czytaniu.

W odniesieniu do drugiego celu pracy przeprowadzono analizę na grupie 120 uczestników przy użyciu statystyki Bayesowskiej. Jej wyniki nie dostarczyły dowodów wskazujących na różnice między grupami w żadnym z testowanych biomarkerów EEG (nachylenie widma oraz moc sygnału w paśmie beta) zarówno w stanie spoczynku, jak i podczas słuchowego zadania językowego. Zaobserwowano jednak dodatnią pośrednią zależność między mocą w paśmie beta, świadomością fonologiczną i szybkością czytania. Wyniki te nie potwierdzają hipotezy zakładającej, że dysleksja jest następstwem zwiększonej pobudliwości korowej. Podkreśla to potrzebę poszukiwania alternatywnych mechanizmów neuronalnych związanych z trudnościami w czytaniu. Ponadto zaobserwowane różnice płciowe w integracji multisensorycznej wskazują na możliwość odmiennych mechanizmów poznawczych i neuronalnych u mężczyzn i kobiet z dysleksją, co powinno zostać uwzględnione w przyszłych teoriach dysleksji.

ABBREVIATIONS

ADHD – attention-deficit/hyperactivity disorder

AG – angular gyrus

ARHQ – Adult Reading History Questionnaire

ASD – autism spectrum disorder

AUC – area-under-the-curve

CP – cumulative probability

E/I – excitatory/inhibitory

EEG – electroencephalography

ERP – event-related potential

GABA – gamma-aminobutyric acid

GFP – global field power

Glu – glutamate

ICA – independent component analysis

IFG – inferior frontal gyrus

ISI – inter-stimulus interval

MRS – magnetic resonance spectroscopy

PSD – power spectral density

RAN – rapid automatized naming

RMI – race model inequality

RT – reaction time

RTE – redundant-target effect

SAS – sluggish attentional shifting

SMG – supramarginal gyrus

STG – superior temporal gyrus

STS – superior temporal sulcus

VWFA – visual word form area

1. INTRODUCTION

Dyslexia is a developmental disorder characterized by specific and persistent difficulties in learning to read, manifested in lowered reading accuracy, fluency, and comprehension (World Health Organization, 2019). This specific difficulty cannot be explained by a decline in general intelligence level, comorbid neurological disorders, sensory disability (vision or hearing impairment), or inadequate educational opportunities (World Health Organization, 2019). Dyslexia is diagnosed in every language (both in alphabetic and logographic writing systems) and its prevalence is estimated to be around 7-12% of the general population (Snowling & Melby-Lervåg, 2016; Yang et al., 2022), with higher occurrence in males than in females (Di Folco et al., 2022; Quinn & Wagner, 2015; Yang et al., 2022). Furthermore, the prevalence increases to 45% among children with a familial history of dyslexia (Snowling & Melby-Lervåg, 2016), i.e., first-degree relative with a dyslexia diagnosis. This suggests a substantial genetic component, with some candidate genes associated with dyslexia identified so far (Becker et al., 2017; Bieder et al., 2020; Fisher & DeFries, 2002). It also frequently co-occurs with other developmental disorders, including attention-deficit/hyperactivity disorder (ADHD), which has a comorbidity rate of 18-42% (Germanò et al., 2010); developmental language disorder, with a 43-58% comorbidity rate (Snowling et al., 2019); and dyscalculia, with around 40% comorbidity rate (Wilson et al., 2015). Additionally, dyslexia is associated with secondary consequences in social and emotional domains (Livingston et al., 2018; Nevill & Forsey, 2023), highlighting the importance of research on the mechanisms of dyslexia from a public health perspective.

1.1. The cognitive basis of dyslexia

Over the last decades, multiple theories of dyslexia have been proposed, with different underlying mechanisms postulated. The leading cognitive theory indicates a deficit in phonological processing, i.e., abilities enabling recognition and manipulation of language sounds (phonemes), as a core factor of reading difficulties (Snowling, 1998; Stanovich, 1988; Wagner & Torgesen, 1987). Specifically, the theory predicts that efficient reading process relies on: 1) phonological awareness (recognition of the language's sound structure), 2) phonological recoding (recoding written symbols into their sound representations), and 3) phonological memory (maintaining phonological information in the working memory efficiently) (Wagner & Torgesen, 1987). To date, phonological deficits in dyslexia have been well-established in studies encompassing different age groups (Melby-Lervåg et al., 2012; Reis et al., 2020) and various languages (Carioti et al., 2021; Peng et al., 2017; Reis et al., 2020). Studies on Polish participants also support this notion, as deficits in phonological awareness and phonological memory have been observed in Polish children (Dębska et al., 2022; Krasowicz-Kupis et al., 2009) and adults with dyslexia (Bogdanowicz et al., 2014). Moreover, broader verbal working memory deficits, beyond phonological material, have also been reported in Polish adults with dyslexia (Łockiewicz et al., 2012). As an extension of the phonological hypothesis, the double-deficit hypothesis indicates that deficiencies in both phonological processing and rapid automatized naming (RAN; naming aloud as quickly as possible a series of familiar visual stimuli such as objects, colors, letters, or digits) independently contribute to the emergence of dyslexia (Wolf & Bowers, 1999). Although there is evidence pointing to the separate influence of these two factors (Badian, 1997; Lovett et al., 2000; Torppa et al., 2012), there are also studies indicating that naming speed is not independent of phonology but rather relies on fast alignments between phonological codes and corresponding visual symbols (Pennington et al., 2001; Vaessen et al., 2009; Vukovic & Siegel, 2006). Regardless of the basis of this ability, impairments in RAN are frequently observed in individuals with dyslexia across different languages and age groups (Araújo & Faísca, 2019; Chen et al., 2021). Deficits in RAN have also been reported in Polish children (Dębska et al., 2022; Krasowicz-Kupis et al., 2009) and adults with dyslexia (Bogdanowicz et al., 2014), with the evidence supporting the independent contribution of RAN and phonological skills in the Polish language (Dębska et al., 2022; Krasowicz-Kupis et al., 2009).

Another line of research suggested impairments at a more basic level in either auditory or visual domain. The rapid auditory processing theory posits that the phonological deficit in dyslexia is a consequence of a deficiency in the primary perception of rapidly presented short sounds (Tallal et al., 1993). Although a recent meta-analysis indicates impairments in various non-linguistic auditory tasks in dyslexia (McWeeny & Norton, 2024); the relationship between auditory perception and the development of phonological and reading skills still requires further investigation due to heterogeneous findings depending on the phonological task used (Witton et al., 2020). On the other hand, the magnocellular theory emphasizes the role of visual perception impairments in difficulties with processing letters and words during reading (Livingstone et al., 1991; Stein & Walsh, 1997). According to this theory, individuals with dyslexia have reduced contrast sensitivity at low spatial frequencies, lower motion sensitivity, and visuospatial attention difficulties due to disruptions in the magnocellular pathway and dorsal visual system (Stein & Walsh, 1997). In this matter, cumulative evidence is mixed. Deficits in motion detection (Benassi et al., 2010) and visual attention span (Tang et al., 2023) are generally observed; however, the effects differ depending on the specific task employed. Also, individuals with dyslexia tend to have poorer visuo-spatial attention, though their performance exhibits greater variability than those of typical readers (Chamberlain et al., 2018).

Although the magnocellular theory predicts attentional deficits primarily in the visual domain as a consequence of lower-level dysfunctions in visual perception, more general attentional deficits across sensory modalities have also been proposed under the sluggish attentional shifting (SAS) framework (Hari & Renvall, 2001). Based on the SAS account, dyslexic readers experience difficulties in shifting attention between fast transitions of stimulus sequences in every modality, linking predictions of rapid auditory processing and magnocellular theory (Hari & Renvall, 2001). Empirical evidence supporting this hypothesis is mixed. For instance, one study indicated worse performance in both visual and auditory attentional shifting tasks among participants with dyslexia (Lallier et al., 2010). However, the other one, contrary to the amodal predictions of the SAS, identified consistent differences in auditory, but not visual tasks (Lallier et al., 2009). Furthermore, some studies demonstrate that dyslexic readers do not exhibit impairment in shifting attention at the cognitive level *per se*, but rather are characterized by slower speed of processing (Abbott et al., 2015; Stoet et al., 2007).

Given these various mechanisms possibly contributing to dyslexia, the multiple deficit model proposes that developmental disorders originate from the interaction of numerous risk factors, rather than attributing them to a single cause (McGrath et al., 2020; Pennington, 2006). In this context, one study characterized three subtypes of dyslexia based on different profiles of cognitive deficits in: 1) phonological awareness, 2) visual attention, or 3) phonological, auditory discrimination, and magnocellular motion sensitivity tasks (Heim et al., 2008). In a sample of Polish children with dyslexia, a phonological deficit was the most prevalent (found in 51% of the children), followed by a deficit in RAN (26%); and both of these deficits co-occurred in 14% of the children (Dębska et al., 2022). Deficits in visual attention and non-linguistic auditory tasks were sporadic and mostly coexisted with impairments in phonological skills and RAN (Dębska et al., 2022). Moreover, the authors conclude that even if deficits in phonological processing and RAN are weak but co-occur, they may still lead to the development of dyslexia (Dębska et al., 2022), which aligns with the multiple deficit model (McGrath et al., 2020; Pennington, 2006). Interestingly, despite having significant impairment in reading, 26% of the children did not present dysfunction in any of the selected tasks (Dębska et al., 2022). Similar results were obtained in a study on English-speaking participants, which indicated that a phonological deficit was present in around half of the individuals with dyslexia, while 40% did not exhibit a deficit in any of the tested skills (Pennington et al., 2012), suggesting that other cognitive mechanisms could be explored. Since reading requires associating auditory and visual information (combining a word's sound with its written form) another potential risk factor of dyslexia may involve deficits in the integration of multisensory audiovisual inputs (Hahn et al., 2014).

1.2. Multisensory integration in dyslexia

The initial evidence of disrupted non-linguistic multisensory integration in dyslexia comes from Birch & Belmont (1964), who found that boys with dyslexia performed worse than control boys on a task requiring them to match sequences of auditory tones to visual patterns. This finding was later expanded to demonstrate a general deficit in temporal processing across both unimodal (auditory and visual) and cross-modal (audiovisual) tasks in children with dyslexia (Rose et al., 1999). Subsequent research has also typically assessed participants' temporal abilities using simultaneity judgment and temporal order judgment tasks. In these tasks, two stimuli are presented with different inter-stimulus intervals (ISIs), and participants have to determine whether the stimuli were presented simultaneously (simultaneity judgment task) or which stimulus appeared first (temporal order judgment task); and poorer temporal abilities are indicated by longer ISIs needed for correct responses (Colonius & Diederich, 2020; García-Pérez & Alcalá-Quintana, 2012). Results from these paradigms demonstrate that individuals with dyslexia perform worse not only in audiovisual condition (Hairston et al., 2005) but also in audiotactile and visuotactile ones (Laasonen et al., 2002), suggesting a potential broad impairment in multisensory integration across different sensory modalities. When accuracy in auditory, visual, and audiovisual versions of the temporal order judgment task was assessed, participants with dyslexia were less accurate than controls in all three tasks (Liu et al., 2019). Furthermore, a meta-analysis of both unisensory and multisensory temporal abilities in dyslexia points out large effect sizes for deficits in visual and auditory conditions, and a moderate effect size in multisensory conditions (Meilleur et al., 2020).

Therefore, since dyslexic readers show impairments also in the unisensory temporal tasks, it has been suggested that the reported differences in the multisensory condition might stem from a general dysfunction of temporal skills, rather than a multisensory integration deficit itself (Gori et al., 2020). Some other studies have also identified deficits in multisensory spatial attention tasks in dyslexia under the SAS framework (Facoetti et al., 2010; Krause, 2015); however, these results might also be influenced by a general attentional deficit.

Another paradigm for studying multisensory integration is the redundant-target effect (RTE) task, in which both unisensory (e.g., an auditory tone and a visual pattern) and multisensory stimuli (simultaneous presentation of tone and pattern) require simple behavioral detection. Using this approach, several lines of research have shown that participants' reaction times (RTs) are faster in multisensory compared to unisensory conditions (Colonius & Diederich, 2017). In the assessment of the multisensory integration effect from the RTE task, Miller's race model inequality (RMI) is typically employed (Miller, 1982). According to the RMI, a speeded behavioral reaction in the multisensory condition might stem from two sensory inputs processed independently, from which the one processed faster induces the motor response, i.e., 'wins the race'. In this case, the race model holds, meaning that RTs in the multisensory condition can be predicted by RTs in unisensory conditions; and no integration of the stimuli in sensory processing can be recognized. However, when gains in response under multisensory conditions are greater than predicted by RTs from unisensory conditions, the race model is violated, and the integration of stimuli can be asserted (Miller, 1982). To date, this approach has only been applied once in dyslexia research. Using simple non-linguistic stimuli (white noise bursts and Gabor patches), Harrar and colleagues (2014) demonstrated that participants with dyslexia exhibited slower RTs than typical readers across all conditions and benefited less from multisensory inputs than the control group when the RMI was evaluated. Furthermore, the magnitude of multisensory integration correlated with the discrepancy scores between literacy and non-verbal abilities (Harrar et al., 2014), supporting the importance of multisensory integration deficits in dyslexia.

Multisensory integration can also be studied at the electrophysiological level using event-related potentials (ERPs). In this method, neuronal activity in multisensory trials is typically compared to the summed activity in unisensory trials within the P1-N1-P2-N2 complex (early components related to sensory processing). Differences in neural responses under these conditions are interpreted as divergent processing of the stimuli when presented simultaneously or alone (Brandwein et al., 2011; Molholm et al., 2020). These differences could be expressed either as sub-additive effect (when the sum of unisensory conditions elicits a greater neuronal response than the multisensory ones) or super-additive effect (multisensory condition eliciting a greater response than the sum of unisensory conditions), with both being reported as multisensory integration indices in human research (Stevenson et al., 2014). Up to now, such ERP studies on multisensory integration in dyslexia are limited.

One study using linguistic stimuli (syllables) found that in the P1 component, the sub-additivity effect was present in the dyslexic, but not in the control group (Kronschnabel et al., 2014). However, the authors suggested that this difference could be attributed to delayed neuronal responses to unimodal auditory and visual stimuli in the dyslexic participants rather than between-group differences in multisensory integration. At the behavioral level, no differences in mean RTs between controls and dyslexics were found (Kronschnabel et al., 2014), although specific gain in RTs in multisensory condition was not evaluated. Conversely, another study did not identify any ERP differences using the standard McGurk effect task and the simultaneity judgment task with syllable stimuli, although behaviorally, the dyslexic group performed worse than controls in both the simultaneity judgment task and the visual condition of the McGurk task (Francisco, 2017). Moreover, in a task with 1000 Hz tones and visual flashes presented alone or simultaneously, where participants (males only) assessed whether stimuli were presented at the same time or not, dyslexic males exhibited delayed P2 and P3 components in both visual-alone and multisensory conditions (Breznitz & Meyler, 2003). Direct comparisons between neural responses to multisensory and the sum of unisensory trials were not conducted, however. Behaviorally, dyslexic males performed slower than controls in the multisensory condition (Breznitz & Meyler, 2003), though the facilitation of RTs based on the RMI was not assessed.

These heterogeneous findings might be attributed to differences in tasks and stimuli, as well as to the uneven number of male and female participants in the studied cohorts. Indeed, a meta-analysis of temporal skills in dyslexia (both unisensory and multisensory) indicates that studies that did not match participants in terms of sex provided greater effect sizes than sex-matched studies (Meilleur et al., 2020). Moreover, in autism spectrum disorder (ASD), which is another developmental disorder more commonly diagnosed in males, sex differences were identified in a multisensory speech processing task, with girls with ASD performing better than boys (Ross et al., 2015).

Nevertheless, potential sex differences have not been directly evaluated in any of the multisensory research in dyslexia, although some evidence indicates such differences in other domains.

1.3. Sex differences in dyslexia

Dyslexia is diagnosed in males around 1.6 to 2.4 times more frequently than in females (Di Folco et al., 2022; Quinn & Wagner, 2015; Yang et al., 2022). Moreover, results from a large English-speaking sample indicate that males compared to females have lower mean scores and greater variance in reading skills and are overrepresented in the lower tail of the distribution (Arnett et al., 2017), which explain the greater proportion of males with a dyslexia diagnosis. Regarding general sex differences in reading-related cognitive tasks, males tend to perform worse than females in processing speed and inhibitory control, but better in verbal reasoning tasks (Arnett et al., 2017). Interestingly, no differences in phonological awareness or working memory were found (Arnett et al., 2017).

When both the effects of sex and dyslexia status were evaluated in Spanish-speaking children, the main effect of sex indicated that females outperform males in speech perception, syntactic processing, homophone comprehension, and word naming accuracy, while males outperform females in working memory tasks (Jiménez et al., 2011). However, in RAN and reading fluency tasks, the interaction between group and sex revealed that differences between females and males were found in the control, but not in the dyslexic group, suggesting against sex-specific cognitive profiles in dyslexia (Jiménez et al., 2011). Additionally, data from a Chinese sample indicate that males with dyslexia perform better than females in the visual memory test, while no differences were identified in RAN, visual perception, or phonological and orthographic tasks (Chan et al., 2007).

Beyond the cognitive level, evidence suggests that genetic risk factors associated with dyslexia may differ between sexes. One study on a German sample indicated that specific variants located on three regions of the *dyslexia-susceptibility-1-candidate-1* gene were associated with a higher odds ratio for dyslexia only in females (Dahdouh et al., 2009). Additionally, data from a Chinese sample suggest that polymorphisms in two regions of the *contactin-associated protein-like 2* gene are linked to a lower risk of dyslexia in females but not in males (Gu et al., 2018). Furthermore, it was postulated that dyslexia is associated with sex-specific neural underpinnings due to the differential role of sex hormones in fetal brain development (Geschwind & Galaburda, 1985). Up to now, some studies have indeed reported such differences at the neural level (Krafnick & Evans, 2019), with sex being identified as a potential factor for mixed findings in research on dyslexia (Ramus et al., 2018). Before describing these differences in detail, a general outline of the neural basis of dyslexia will be presented.

1.4. The neural basis of dyslexia

The neural network for reading encompasses multiple brain structures located predominantly in the left hemisphere. These regions are organized across occipito-temporal, temporo-parietal, and frontal cortices, each associated with different stages of the reading process (Schlaggar & McCandliss, 2007). The left ventral occipito-temporal cortex is specifically engaged in the recognition of written words and region located in the left fusiform gyrus, named the Visual Word Form Area (VWFA), shows greater activation for letters and words than for other visual stimuli (Dehaene & Cohen, 2011). The VWFA is therefore considered crucial for the recognition of visual word patterns while gaining expertise in reading (McCandliss et al., 2003). Several meta-analyses of functional imaging studies indicate that hypoactivation in the VWFA is consistently observed in dyslexia across different languages and age groups (Maisog et al., 2008; Martin et al., 2016; Richlan et al., 2011). Also, one meta-analysis identified a specific convergence of both functional and anatomical differences in dyslexia within the left fusiform gyrus (Linkersdörfer et al., 2012), the other one, however, did not identify a similar overlap in this region (Yan et al., 2021). Data from the Polish sample align with the reported pattern of reduced activation. A longitudinal study on Polish children found hypoactivation in the VWFA in children with dyslexia, compared to both age-matched and reading-matched control groups, providing evidence for a specific atypical neurodevelopmental trajectory in dyslexia that cannot be solely explained by lower reading expertise (Chyl et al., 2019).

On the other hand, heteromodal areas in the left temporo-parietal cortex, namely the superior temporal sulcus/gyrus (STS/STG) and two gyri forming the inferior parietal lobule: supramarginal gyrus (SMG), and angular gyrus (AG), are involved in decoding written words through crossmodal mappings between words' sounds and their visual representations (Pugh et al., 2001). The STS is activated by both visual and auditory linguistic inputs and is particularly important for processing established correspondences between letters and speech sounds (Van Atteveldt et al., 2004). This was also demonstrated in the Polish language, as a study on children during their first two years of formal education showed increased activation in the left superior temporal cortex for letters and speech sounds over time (Beck et al., 2024). Interestingly, this region was also associated with greater activation in blind individuals reading Braille (Beck et al., 2023), pointing to its universal role in processing multisensory linguistic inputs. The SMG is also involved in phonological processing (Hartwigsen et al., 2010; Sliwinska et al., 2012), specifically during learning grapheme-phoneme associations (Romanovska & Bonte, 2021), with the suggested mechanism of the domain-general working memory recruitment (Deschamps et al., 2014). Concurrently, the activity in AG is associated with retrieving semantic information from the processed inputs (Binder & Desai, 2011). Within this network, meta-analyses report diminished activity in the STS in dyslexia, either in both the left and right hemispheres (Maisog et al., 2008) or specifically in the left STS in adults with dyslexia rather than children (Richlan et al., 2011). Furthermore, a meta-analysis of structural studies identified only two regions with a reduction of gray matter volume associated with dyslexia – the left STS and right STG (Richlan et al., 2013). Additionally, studies which evaluated convergence between functional and structural alterations in dyslexia found clusters of overlap within the left STG (Yan et al., 2021) or left SMG (Linkersdörfer et al., 2012). Also, data from Polish children suggest different patterns of activation in the left STG in children with a familial risk of dyslexia, compared to those without such risk (Plewko et al., 2018). Regarding other regions of the temporo-parietal cortex, the referenced meta-analyses report hypoactivation either specifically in the left SMG in dyslexia (Maisog et al., 2008) or more generally in the left inferior parietal lobule, without distinguishing between the SMG and AG (Martin et al., 2016; Richlan et al., 2011).

Finally, the left inferior frontal gyrus (IFG) is engaged in many language-related functions, such as phonological processing both in reading and speech production (Burton, 2001), verbal working memory (Chein et al., 2002), semantic processing (Fiez, 1997), auditory attention (Pugh et al., 1996) and articulatory processes both in overt and silent reading (Okada et al., 2018; Price, 2012). The activity in the left IFG increases when children learn to read (Turkeltaub et al., 2003) and is greater when reading low-frequency words than high-frequency words (Sánchez et al., 2023), reflecting the IFG's role in phonological decoding during reading. Although some works demonstrated increased activation of the left IFG in dyslexia (Georgiewa et al., 2002; Hoeft et al., 2007; Shaywitz et al., 1998), meta-analyses rather point to the decreased activity (Maisog et al., 2008; Martin et al., 2016). Furthermore, when children and adults were evaluated separately, hypoactivation in the left IFG was found only in adults with dyslexia, mirroring the pattern observed for the left STS (Richlan et al., 2011). Interestingly, a meta-analysis of activation patterns separately for reading real words and pseudowords identified significant age-related effects only for pseudowords (Zhang & Peng, 2022). Specifically, in the left STS, greater hypoactivation in dyslexia was linearly associated with age, while in the left IFG, the relationship was quadratic, with greater hypoactivation observed until the age of 22 (Zhang & Peng, 2022). No such age-related effects were found in general hypoactivation pattern observed in dyslexia for reading real words (Zhang & Peng, 2022). In the context of Polish language, results from a longitudinal study on children suggest specific dyslexia-related hypoactivation in the left IFG, similar to the pattern observed in the VWFA (Chyl et al., 2019).

Besides these regions, functional studies often indicate that reading is associated with activity in the cerebellum, thalamus, and insula (Lee & Stoodley, 2024; Li et al., 2022), although these structures are not typically recognized as part of the canonical reading network. Yet, some meta-analyses suggest differences in activity in these regions in dyslexia, with reports of both hypo- and hyperactivation (Linkersdörfer et al., 2012; Maisog et al., 2008; Yan et al., 2021). Moreover, white matter integrity between reading-related cortical structures might form another important input in the efficient reading process (Thiebaut de Schotten et al., 2014; Yeatman et al., 2012), however cumulative evidence for dyslexia-related effects in these measures remains mixed. Results from one meta-analysis indicate that lower white matter integrity in the left temporo-parietal cortex (namely in the left arcuate fasciculus and left corona radiata) is the most consistent finding across studies on dyslexia (Vandermosten et al., 2012); the other one, however, did not find any systematic differences between dyslexic and typical readers (Moreau et al., 2018).

Regarding previously described sex differences in dyslexia, relatively few MRI studies have included sex as a variable of interest. However, those that have included it have identified such differences at the neural level. For instance, one study noted a reduction of gray matter volume in dyslexic males in the left temporo-parietal cortex, while in females, differences were observed outside the canonical reading network, predominantly in the right hemisphere (Evans et al., 2014). In contrast, a reduction of cortical thickness in the individually localized language-sensitive left ventral occipito-temporal cortex was identified only in girls with dyslexia (Altarelli et al., 2013).

Furthermore, some evidence suggests differences in left hemispheric white matter integrity (Gupta et al., 2024) or asymmetry of the planum temporale (Altarelli et al., 2014), specifically in males with dyslexia. A recent study also found a significant correlation between greater left-lateralized activity in the magnocellular division of the thalamus during a visual task and a slower completion time on the letters and digits subtests of the RAN task in males with dyslexia, but not in females (Müller-Axt et al., 2025). Although these findings still require further evaluation, they highlight the complexity of the neural basis of reading difficulties and the importance of considering sex-specific effects in dyslexia research.

1.5. Neural noise hypothesis of dyslexia

Given this multifaceted nature of dyslexia, the neural noise hypothesis is one of the newest propositions predicting reading difficulties at multiple levels – from genes and neural mechanisms to cognitive and behavioral manifestations (Hancock et al., 2017). It is particularly appealing as it provides explanation for deficits across a variety of domains. Specifically, the hypothesis posits that risk genes associated with dyslexia disrupt neuronal migration and increase glutamatergic signaling at the cellular level. This, in turn, leads to heightened cortical excitability, causing the 'neural noise’ – an imbalanced activity between excitatory and inhibitory neural circuits (Hancock et al., 2017). At the level of neurochemistry, neural noise is therefore defined as asynchrony in signaling between the main excitatory (glutamate, Glu) and main inhibitory (gamma-aminobutyric acid, GABA) neurotransmitters. This reduced synchronization supposedly causes greater variability in neural firing and consequently disrupts the encoding of sensory representations leading to impairments in phonological awareness, multisensory integration, and lexical access and generalization (i.e., RAN), which contribute to the emergence of dyslexia (Hancock et al., 2017). The hypothesis specifically predicts that perisylvian regions of the cortex, including superior temporal cortex, are affected by increased neural noise, resulting in difficulties with these cognitive skills. However, a more speculative pathway between neural noise in the visual cortex and disruptions in orthographic processing has also been suggested (Hancock et al., 2017). A schematic model illustrating the hypothesis's predictions is presented in Figure 1.

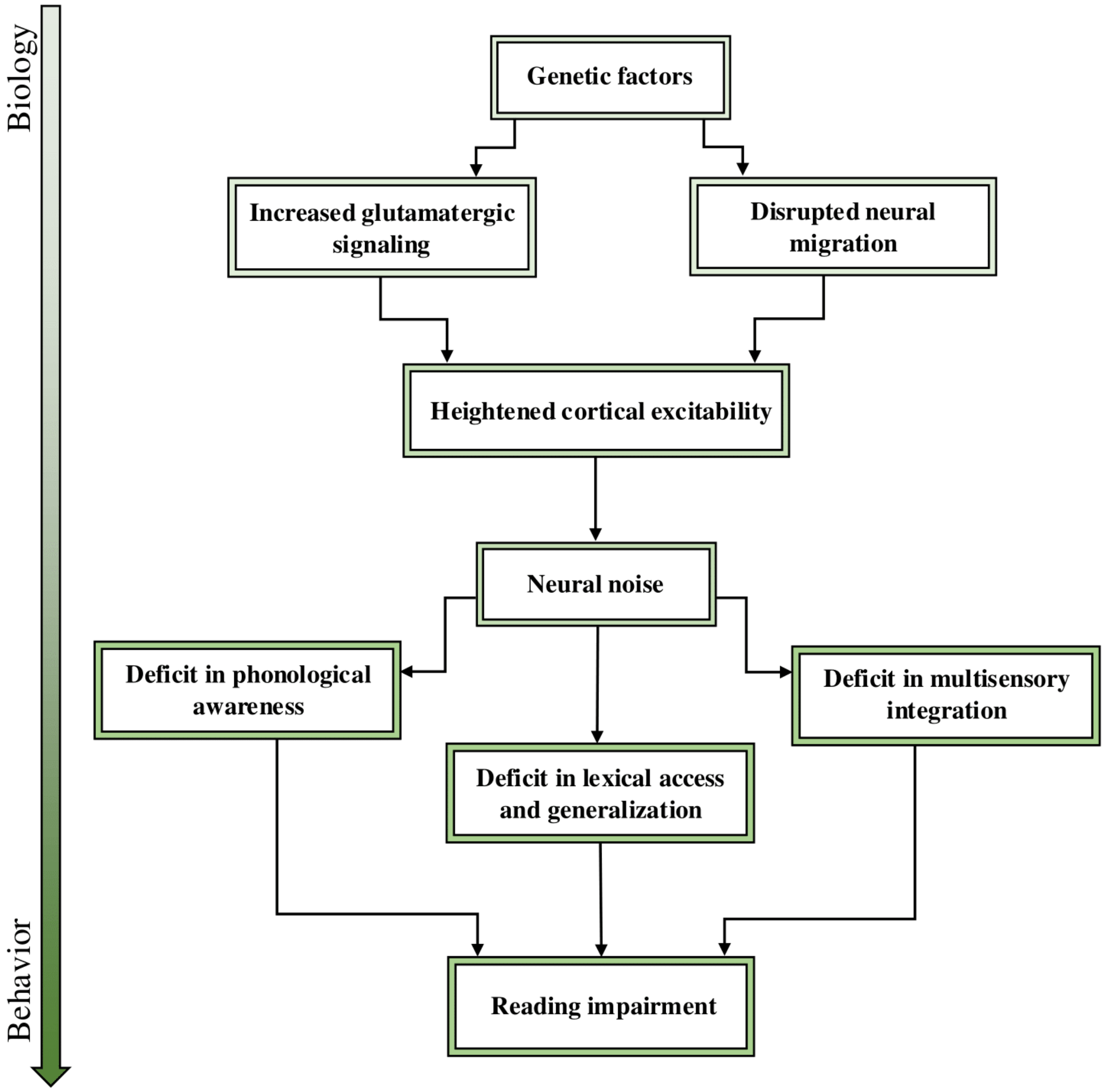

Figure 1. *Schematic representation of the neural noise hypothesis of dyslexia (adapted from Hancock et al., 2017).*

To date, research on excitatory and inhibitory (E/I) brain activity in dyslexia has primarily focused on measuring local concentrations of Glu and GABA using magnetic resonance spectroscopy (MRS), yielding mixed results. For instance, one study found that higher Glu levels in the midline occipital cortex correlate with poorer reading performance in children (Pugh et al., 2014). In contrast, another study reported the opposite relationship, with increased Glu levels in the anterior cingulate cortex associated with better phonological skills (Lebel et al., 2016). Moreover, following an intervention program focused on executive functions, Glu levels in the anterior cingulate cortex significantly decreased in children with dyslexia (Cecil et al., 2021). Regarding GABA, evidence indicates that higher GABA levels in the midline occipital cortex are associated with slower RTs in a multisensory linguistic task in children (Del Tufo et al., 2018) and that higher GABA levels in the left IFG are linked to worse verbal fluency in adults (Nakai & Okanoya, 2016). Importantly, there are also studies reporting non-significant dyslexia-related effects in either Glu or GABA concentration in the visual and left temporo-parietal cortex in both children and adults (Kossowski et al., 2019) and in Glu levels in the anterior cingulate cortex in children (Horowitz-Kraus et al., 2018).

Non-invasive measurement of the E/I balance can also be obtained from the electroencephalography (EEG) signal, which provides various estimations of E/I brain activity (Ahmad et al., 2022). The EEG signal in a frequency domain can be decomposed into periodic activity manifested as peaks in power at specific frequency ranges (oscillations) and aperiodic, broadband activity characterized by an exponential decrease in power with increasing frequency (1/f signal) (Donoghue et al., 2020; He, 2014). Differences between periodic and aperiodic activity are presented in Figure 2. For many years, only the oscillatory activity was thought to be physiologically relevant (Buzsáki et al., 2012), while the 1/f signal was considered as background noise. Recent studies, however, have challenged this assumption by showing significant differences in the 1/f signal modulated for instance by task requirements (Cross et al., 2022; Gyurkovics et al., 2022).

Recent works also highlight the importance of the aperiodic 1/f signal in estimating E/I brain activity (Ahmad et al., 2022). The 1/f signal is described by two values – the exponent, which quantifies the steepness of the EEG power spectrum, and the offset, representing the uniform shift in power across frequencies (Donoghue et al., 2020). While a higher aperiodic offset has been linked to increased neuronal spiking rates (Manning et al., 2009), the exponent seems to be particularly relevant for the E/I balance assessment (Gao et al., 2017). Research indicates that lower exponent (flatter signal) reflects a shift towards excitation over inhibition, as established by the ratio of AMPA to $GABA_A$ synapses in the CA1 region of the rat hippocampus, computational models of local field potentials (Gao et al., 2017), and recordings under anesthetic drugs that modulate Glu or GABA receptors (e.g., ketamine and propofol) in humans and monkeys (Gao et al., 2017; Muthukumaraswamy & Liley, 2018; Waschke et al., 2021). However, pharmacological studies in this context have not always yielded consistent results. For instance, one study reported an expected increase in the aperiodic exponent following propofol administration, whereas the decrease in the exponent after ketamine was observed only in the 20-40 Hz range, with no significant effect across the entire 1-40 Hz spectrum (Colombo et al., 2019). In contrast, another study noted that while some drugs alter the exponent in line with the predicted E/I ratio, others have no effect on the exponent or even modulate it in a direction opposite to the prediction (Salvatore et al., 2024). Furthermore, the exponent appears to be influenced by different drugs that impact receptors other than glutamatergic and GABA-ergic ones (Muthukumaraswamy & Liley, 2018; Zsido et al., 2022), making it a global, indirect biomarker of the E/I balance (Ahmad et al., 2022). Although the exponent is typically considered an E/I balance biomarker, one pharmacological study has also demonstrated that differences in the exponent often accompany differences in the offset (Salvatore et al., 2024), and these two aperiodic measures are frequently correlated (Euler et al., 2024; McSweeney et al., 2021; Pei et al., 2023).

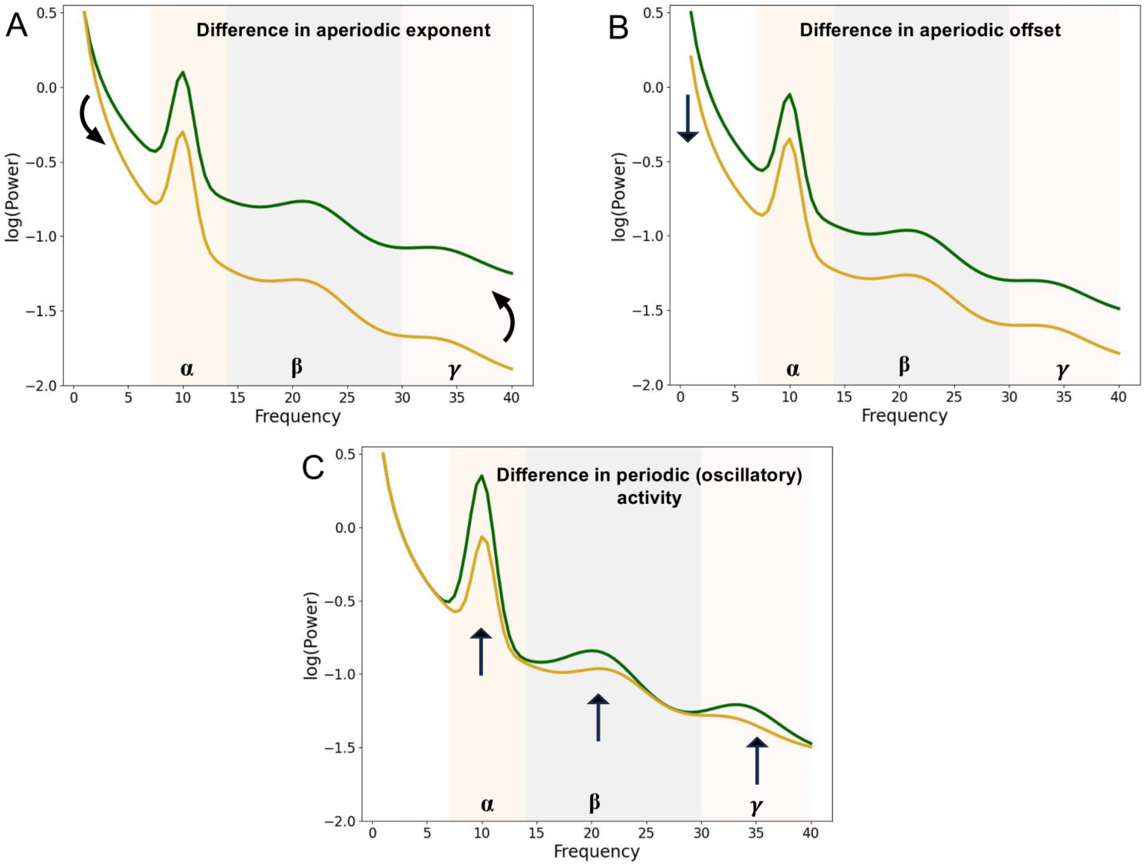

Figure 2. *Visualization of simulated EEG power spectra showing differences in **(A)** aperiodic exponent, indicating the steepness of the spectrum; **(B)** aperiodic offset, indicating a uniform shift in power across frequencies; and **(C)** periodic (oscillatory) activity, manifested as peaks in power within specific frequency bands (adapted from Cellier et al., 2021).*

Regardless of the specific cellular mechanisms driving variability in the 1/f signal, differences in the aperiodic exponent have been linked to conditions associated with alterations in E/I balance. For instance, consistent age-related changes have been observed. The exponent decreases during the first seven months of life (Schaworonkow & Voytek, 2021), throughout early adolescence (McSweeney et al., 2021), and is lower in young adults compared to children (Cellier et al., 2021), as well as in older compared to younger adults (Voytek et al., 2015). Furthermore, differences in the aperiodic exponent have been reported in neurodevelopmental disorders. A lower exponent (flatter slope) has been observed in children and adolescents with ADHD (Pertermann et al., 2019; Ostlund et al., 2021) and in children with ASD, though only in those with a concurrent decline in intelligence level (Manyukhina et al., 2022). In contrast, a higher exponent (steeper slope) has been reported in adults with schizophrenia (Molina et al., 2020). The aperiodic exponent has been also shown to be a better predictor of schizophrenia than typical narrow-band oscillatory activity (Peterson et al., 2023). However, these findings are not always consistent, as a reversed pattern, with a higher exponent observed in children with ADHD, has also been reported (Robertson et al., 2019), emphasizing the need for further studies to evaluate E/I balance in neurodevelopmental disorders.

Up to now, only one study has examined differences in 1/f signal between typical and dyslexic readers. Turri and colleagues (2023) demonstrated that adults with dyslexia are characterized by lower aperiodic exponent and offset compared to the control group at rest. However, this difference was significant only in the parieto-occipital, but not in the frontal region. The authors also reported that there was a significant association between word reading speed and offset, but not the exponent, in the dyslexic group (Turri et al., 2023), providing partial support for the neural noise hypothesis. Nevertheless, associations between E/I balance biomarkers and specific cognitive mechanisms underlying dyslexia posited by the hypothesis – phonological awareness, RAN, and multisensory integration (Hancock et al., 2017) – have not been evaluated.

Apart from aperiodic 1/f signal, also beta (~13-28 Hz) and gamma (> 30 Hz) oscillations might be considered E/I balance biomarkers (Ahmad et al., 2022). Greater beta power has been associated with increased GABA-ergic activity following the administration of the GABA agonist benzodiazepine (Jensen et al., 2005) as well as with specific GABA_A receptors in genetic studies (Porjesz et al., 2002). Similarly, greater gamma peak frequency has been associated with increased activity of GABA synaptic currents in computational models (Brunel & Wang, 2003). Moreover, in animal studies, distinct classes of inhibitory GABA-ergic interneurons have been associated with increased beta and gamma power, respectively (Chen et al., 2017). Therefore, in line with the neural noise hypothesis, which predicts greater cortical excitability (Hancock et al., 2017), lower beta and gamma power (indicative of decreased GABAergic activity), would be expected in individuals with dyslexia.

However, research on such oscillatory E/I balance biomarkers in dyslexia remains mixed. Regarding beta activity at rest, several studies indicate non-significant effects of dyslexia status on beta power (Babiloni et al., 2012; Fraga González et al., 2018; Xue et al., 2020), although one study revealed that resting-state beta power in boys with dyslexia was lower than in control boys (Fein et al., 1986). Additionally, Turri and colleagues (2023) reported lower beta power in the dyslexic group compared to controls after adjusting for aperiodic activity. They also found a significant association between the number of reading errors and aperiodic-adjusted beta power, an effect observed exclusively in the dyslexic group (Turri et al., 2023). In task-related results, one study noted a decrease in beta activity in the dyslexic group during various linguistic tasks (Spironelli et al., 2008). Conversely, another study reported increased beta power during both phonological and visual tasks in children with dyslexia (Rippon & Brunswick, 2000). In terms of gamma activity at rest, some studies report a lack of dyslexia-related differences in gamma power (Babiloni et al., 2012; Lasnick et al., 2023). However, in a study on auditory steady-state responses, the dyslexic group was characterized by a lower gamma peak frequency compared to the control group, although there were no significant differences in gamma power (Rufener & Zaehle, 2021). Importantly, most research on task-related gamma activity in dyslexia has focused on paradigms that evaluate cortical entrainment to auditory stimuli (Lehongre et al., 2011; Marchesotti et al., 2020; Van Hirtum et al., 2019). Although these studies have reported impaired cortical tracking of gamma frequencies in dyslexia, which aligns with the proposed reduced encoding of sensory stimuli in the neural noise hypothesis (Hancock et al., 2017), they do not provide direct evidence of between-group differences in gamma power or peak frequency that would indicate alterations in E/I balance.

To date, research directly evaluating the neural noise hypothesis of dyslexia (Hancock et al., 2017), encompassing both periodic (beta and gamma oscillations) and aperiodic (1/f signal) E/I balance biomarkers, is still limited.

1.6. Summary

Over the years, various cognitive and neural factors associated with dyslexia have been identified. At the cognitive level, deficits in phonological processing are most consistently observed, although they do not account for all variability in reading abilities. This suggests that other cognitive mechanisms are also involved. One such mechanism might be an impairment in multisensory integration. Although studies indicate deficits in multisensory tasks in dyslexia, the paradigms used to study this phenomenon might actually reflect deficits in other abilities, such as temporal skills or attention. Furthermore, potential sex differences may be another important factor contributing to the variability in dyslexia profiles. Although dyslexia is more commonly diagnosed in males, differences in traits associated with reading impairments specifically in males versus females have not been widely evaluated.

At the neural level, multiple neuroimaging studies have reported hypoactivation in the brain's reading network in dyslexia; however, the direct causal mechanisms leading to reading difficulties remain unresolved. The neural noise hypothesis attempts to address this issue by linking predictions regarding both biological and cognitive risk factors of dyslexia. According to this hypothesis, dyslexia is associated with higher levels of Glu and greater cortical excitability, especially in perisylvian areas, leading to cognitive impairments in phonological awareness, RAN, and multisensory integration, which contribute to difficulties in fluent reading. Although E/I activity can be measured non-invasively in the human brain using EEG, studies directly evaluating the proposed neural noise hypothesis of dyslexia using both periodic (beta and gamma oscillations) and aperiodic (1/f signal) biomarkers in relation to specific cognitive factors are lacking.

2. ORIGINAL STUDY

2.1. Aims & Hypotheses

The aim of the study reported in the current thesis was twofold. Firstly, I aimed to investigate both behavioral and neural indices of multisensory integration in dyslexia with particular emphasis on sex-specific effects. This was grounded on a meta-analysis of multisensory and unisensory temporal skills in dyslexia, which suggested discrepancies in reported effect sizes between studies that matched participants in terms of sex or not (Meilleur et al., 2020). However, such potential sex differences have not been directly evaluated in dyslexia so far. Based on previous research on a multisensory speech task in ASD, which reported worse performance in boys (Ross et al., 2015), I expected to find a similar pattern in dyslexia, with males showing greater impairments than females.

Secondly, I aimed to validate the neural noise hypothesis (Hancock et al., 2017) using both periodic (beta and gamma oscillations) and aperiodic (1/f signal) E/I balance biomarkers from the EEG signal. Based on the hypothesis's predictions of increased cortical excitability, I anticipated flatter slopes of the 1/f signal (lower exponent and offset), as well as lower beta and gamma power in participants with dyslexia. Additionally, I wanted to comprehensively test the relationships between E/I balance measures and cognitive mechanisms postulated by the hypothesis through which increased neural noise impacts reading. Building upon the hypothesis's predictions, increased neural noise should be associated with worse outcomes in phonological awareness, RAN, and multisensory integration tasks.

2.2. Methods

The study was conducted between July 2021 and May 2023 at the Laboratory of Language Neurobiology, Nencki Institute of Experimental Biology in Warsaw, Poland, conducted as a part of the OPUS grant from the National Science Centre, Poland (2019/35/B/HS6/01763), awarded to professor Katarzyna Jednoróg. Each participant was invited to the Nencki Institute twice. The first session comprised paper-pencil tasks measuring various reading and reading-related skills, while the second was the EEG session. Additionally, as a part of the project, participants underwent an fMRI study during their first session at the Nencki Institute and a third session involving MRS measurements of Glu and GABA using a 7T scanner at the Ultra-High Field Magnetic

Resonance Lab, ECO-TECH Complex in Lublin, Poland. However, the details of fMRI and MRS sessions will not be discussed here, as they are beyond the scope of this thesis.

In total, 120 Polish adolescents and young adults were recruited – 60 participants with a dyslexia diagnosis obtained in psychological and pedagogical counseling centers, and 60 control participants without reported reading difficulties. Recruitment was conducted through social media postings and telephone contact with participants from previous studies at the Laboratory of Language Neurobiology who had agreed to be contacted. Adolescents and young adults were recruited instead of children because the project involved extended scanning sessions (over one hour) using a 7T MRI scanner, which would be too challenging for children to endure. Due to the lack of standardized diagnostic norms for dyslexia in adults in Poland, participants were recruited to the dyslexic group based on a clinical diagnosis obtained in the past.

All participants were right-handed (self-reported), born at term (after 37 weeks of gestation), with no reported comorbid neurological or psychiatric diagnoses (including ADHD), were not taking any psychoactive medications, had normal or corrected-to-normal vision and did not have hearing impairments. Furthermore, all participants had an IQ higher than 80, measured by the Abbreviated Battery of the Stanford-Binet Intelligence Scale, which includes verbal and non-verbal subscales (Roid et al., 2017).

All 120 participants completed paper-pencil tests and underwent the EEG session for the E/I balance assessment. The participation of 120 individuals was determined by the financial constraints of the project. Additionally, during the EEG session, 88 out of the 120 participants also performed the multisensory integration task. In that case the sample size was determined through a power analysis based on a previous behavioral study on multisensory integration in dyslexia that employed the RTE task (Harrar et al., 2014). The analysis, conducted using G*Power (Faul et al., 2007), indicated that a sample of 44 participants (22 per group) was required to achieve a statistical power of 0.85 ($\alpha = .05$) to detect a large effect size ($d = 0.83$). The sample size was increased to 88 participants to evaluate the interaction effect between group and sex, resulting in 22 participants per subgroup. Hence, to achieve the first aim of the thesis regarding evaluation of potential sex-specific effects in multisensory integration in dyslexia, the results for these 88 participants will be presented first. Subsequently, results from all 120 participants will be presented to address the second objective of the study, which concerns the validation of the neural noise hypothesis.

The study was approved by the institutional review board at the Faculty of Psychology, University of Warsaw, Poland (reference number 2N/02/2021). All adult participants provided written informed consent. For underage participants, written informed consent was obtained from their parents, and verbal assent was provided by the adolescents. Monetary gratification (200 PLN for each session) was given for participation in the study.

2.2.1. Reading and reading-related tasks

All 120 participants completed various paper-pencil tests to evaluate their reading and reading-related skills. Reading speed was assessed by the number of words and pseudowords correctly read aloud in one minute (Szczerbiński & Pelc-Pękała, 2013). RAN was evaluated with subtests of objects, colors, digits, and letters named aloud as quickly as possible (Fecenec et al., 2013). Reading comprehension was assessed by an in-house test comprised of 26 short sentences (e.g., "Pigeon is a bird", "Warsaw is a small village") which participants read silently and had to mark as true or false (Dzięgiel-Fivet et al., 2023) with completion time as the outcome measure. Phonological awareness was tested by a phoneme deletion task (Szczerbiński & Pelc-Pękała, 2013) in which participants had to say a word without a given phoneme (e.g., "marble" without "m" – "arble"; Polish example: "sprawdzam" without "s" – "prawdzam"), and spoonerism tasks: switching phonemes (e.g., "happy song" – "sappy hong"; Polish example: "gotuję jajko" – "jotuję gajko") and syllables (e.g., "modern fashion" – "fadern moshion"; Polish example: "wesoła rodzina" – "rosoła wedzina") between two words (Bogdanowicz et al., 2016). Orthographic awareness was assessed with 28 pairs of pseudowords, where only one was written according to the Polish spelling rules (e.g., "togu" vs. "togó") and participants had to mark the one written correctly (Awramiuk & Krasowicz-Kupis, 2014), with the accuracy/time ratio as the outcome measure.

Visual attention was assessed by a task requiring participants to cross out as many as possible target digits (6 and 9), embedded among non-target digits, in three minutes (Ciechanowicz & Stańczak, 2006). Three measures were calculated from this task: 1) perception speed, reflecting the total number of digits scanned by the participant regardless of accuracy, with a higher score indicating faster perception speed; 2) perceptual discrimination, indicated by the number of non-target digits erroneously crossed out, with a higher score suggesting poorer perceptual discrimination; and 3) selective attention, calculated by the number of target digits omitted by the participant, with a higher score indicating worse selective attention. Furthermore, the forward and backward conditions from the Digit Span subtest of the Wechsler Adult Intelligence Scale-Revised (Wechsler, 1981) were used to evaluate participants' short-term and working memory, respectively. Participants' IQ was measured by the Abbreviated Battery of the Stanford-Binet Intelligence Scale, comprised of both verbal and non-verbal subscales (Roid et al., 2017).

2.2.2. EEG acquisition

EEG data from all 120 participants were collected from 62 scalp-electrodes and 2 ear-electrodes using the Brain Products system (actiCHamp Plus, Brain Products GmbH, Gilching, Germany). The signal was recorded in the BrainVision Recorder Software (Version 1.22.0002, Brain Products GmbH, Gilching, Germany) at a 500 Hz sampling rate. The electrodes were positioned according to the extended 10-20 system, with electrode Cz serving as the online reference and the Fpz as a ground electrode. All electrodes' impedances were set below 10 kΩ.

3. MULTISENSORY INTEGRATION – MATERIALS & METHODS

3.1. Participants

The sample consisted of 88 participants aged between 15.09 and 24.95 years ($M = 19.49$, $SD = 3.30$): 44 diagnosed with dyslexia and 44 typical readers matched in sex, age and family socio-economic status based on mother's and father's years of education (see Table 1).

A univariate ANOVA indicated a significant effect of group ($F(1,84) = 195.57$, $p < .001$, $\eta^2_p = .700$), with the dyslexic group scoring higher ($M = 51.95$, $SD = 10.25$) than the control group ($M = 24.86$, $SD = 7.62$) on the Adult Reading History Questionnaire (ARHQ-PL; Bogdanowicz et al., 2015), where a higher score implies a greater risk of dyslexia. Despite all participants having typical IQ, a significant effect of group was found on the IQ scale ($F(1,83) = 13.33$, $p < .001$, $\eta^2_p = .138$), with the control group ($M = 111.52$, $SD = 9.97$) scoring higher than the dyslexic group ($M = 102.95$, $SD = 11.87$). A significant effect of group was also found on the nonverbal IQ subscale ($F(1,84) = 5.50$, $p = .021$, $\eta^2_p = .061$), with the control group ($M = 11.57$, $SD = 2.56$) scoring higher than the dyslexic group ($M = 10.20$, $SD = 2.92$). The effect of sex and the interaction between group and sex were not significant in any measure (Table 1).

Due to the difference between the dyslexic and control groups in the nonverbal IQ subscale, a repetition of all analyses on a subsample of 80 participants matched for nonverbal IQ, have been reported in the section 4.4. "Results for a subsample of 80 participants (out of 88) matched in nonverbal IQ".

Table 1. *Descriptive statistics for demographic characteristics separately for females and males in dyslexic and control groups (n = 88). For all comparisons, F statistics, p-values (in brackets), and the partial eta squared* (η^2_p) *are provided.*

	DYS F (*n* = 22)		CON F (*n* = 22)		DYS M (*n* = 22)		CON M (*n* = 22)		group *F*(1,84)	η^2_p	sex *F*(1,84)	η^2_p	group*sex *F*(1,84)	η^2_p
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*						
Age	19.43	3.68	19.58	3.49	19.40	3.28	19.54	2.93	0.04 (.840)	.000	0.00 (.966)	.000	0.00 (.994)	.000
Mother's education (years)	16.57	2.95	16.34	2.48	17.75	4.29	17.09	2.02	0.46 (.498)	.005	2.20 (.142)	.026	0.11 (.741)	.001
Father's education (years)	15.81^a	3.42^a	16.77	3.65	16.68	2.64	16.86^a	3.07^a	0.67^c (.414)	.008	0.48^c (.493)	.006	0.32^c (.572)	.004
IQ	104.18	12.59	109.91	10.11	101.67^b	11.23^b	113.14	9.79	13.33^d (**< .001**)	.138	0.02^d (.880)	.000	1.49^d (.226)	.018
Nonverbal IQ (scaled score)	10.27	3.00	10.82	2.56	10.14	2.92	12.32	2.40	5.50 (**.021**)	.061	1.38 (.244)	.016	1.98 (.163)	.023
ARHQ-PL	53.27	8.78	24.68	5.45	50.64	11.60	25.05	9.44	195.57 (**< .001**)	.700	0.34 (.559)	.004	0.60 (.441)	.007

Note. CON – control group; DYS – dyslexic group; F – females; M – males; ARHQ-PL – Polish version of the Adult Reading History Questionnaire.
Boldface indicates statistical significance at $p < .05$ level (uncorrected).
^{a}*n* = 21 (one participant did not provide information about the father's education);
^{b}*n* = 21 (one participant did not attempt a verbal subtest of the scale, thus his overall IQ could not be calculated);
^{c}*F*(1,82); ^{d}*F*(1,83)

3.2. Multisensory integration task

To investigate the multisensory integration effects at both the behavioral and neural levels, the RTE task was employed. Participants were seated in a chair with their heads stabilized on a chin-rest in a dark and electrically shielded cabin and performed a simple reaction time task while the continuous EEG signal was recorded. The task was created using Presentation® software (Version 20.1, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) and involved three conditions: visual-alone, auditory-alone, and audiovisual (see Figure 3). The paradigm was prepared based on previous RTE tasks (e.g., McCracken et al., 2019; Molholm et al., 2020) and adhered to the recommendations outlined by Gondan & Minakata (2016). In the visual-alone condition, a white flash appeared centrally on a black background for 60 ms, while in the auditory-alone condition, a 1000 Hz tone was played binaurally through sound-isolating earphones for 60 ms. The audiovisual condition involved the simultaneous presentation of both auditory and visual stimuli (white flash and 1000 Hz tone) for 60 ms. Participants were instructed to press a button as quickly as possible with their right index finger after any stimulus presentation, using the same response button for all three conditions.

The stimuli from each condition (visual-alone, auditory-alone, and audiovisual) were presented in a random order across 8 blocks of 48 trials, with each block containing 16 trials per condition. Additionally, each block randomly included 2 catch trials without any stimulus presentation to prevent anticipatory responses. At the start of each trial, a white fixation cross appeared centrally for 500 ms, followed by a blank screen with ISIs varying between 1000 and 2500 ms (durations set randomly and equiprobably). After the stimulus presentation (60 ms), a blank screen was presented for 1000 ms to allow the behavioral reaction before the start of the next trial. The entire task comprised 400 trials (128 trials per condition and 16 catch trials) and took approximately 25 minutes to complete. To prevent participants' fatigue and maintain their alertness, 1-minute breaks between blocks were provided.

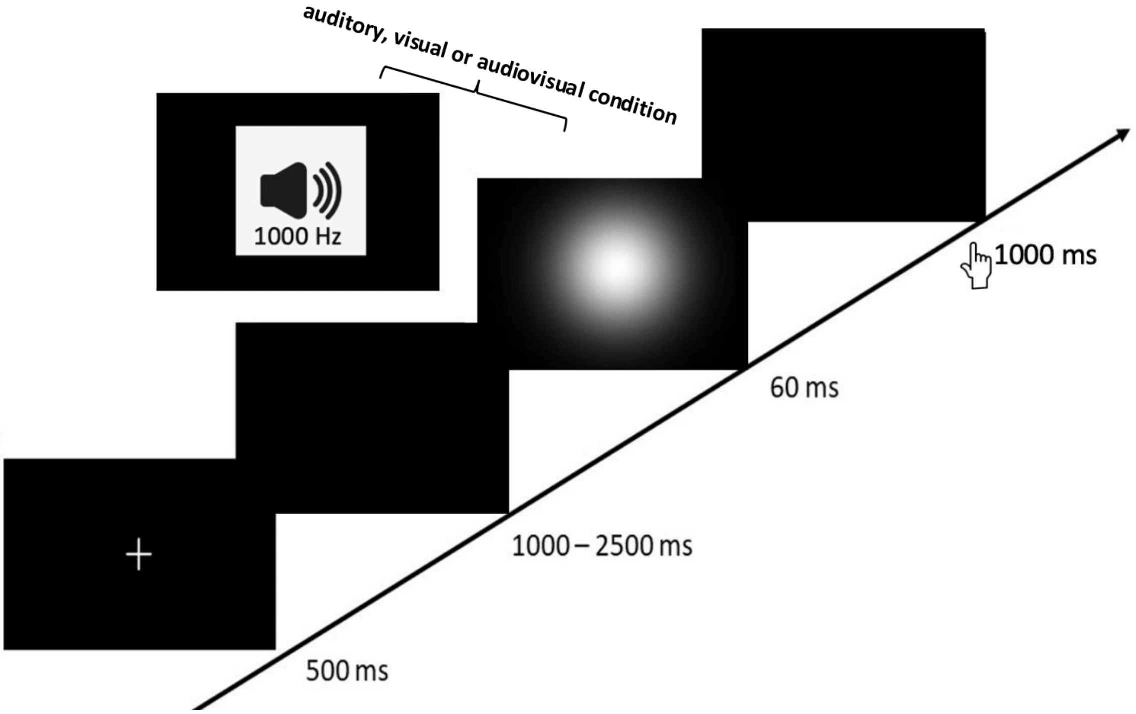

Figure 3. *Schematic illustration of the redundant-target effect task. Each condition (auditory, visual, and audiovisual) was presented 128 times across 8 blocks of trials. Additionally, 16 catch trials (2 per block) with no stimulus presentation were included. Conditions were presented in a random order.*

3.3. Statistical analyses

All statistical analyses were performed on IBM SPSS Statistics v.28. Post-hoc pairwise comparisons were reported with Bonferroni-corrected *p*-values.

3.3.1. Reading and reading-related tasks

For every reading and reading-related task, a separate univariate ANOVA was conducted to test the effect of group, sex, and the interaction between group and sex. Partial eta squared (η^2_p) was reported as the effect size measure. Effect sizes were interpreted as small ($\eta^2_p = 0.01$), medium ($\eta^2_p = 0.06$) or large ($\eta^2_p = 0.14$). Apart from reporting the uncorrected *p*-values, the Bonferroni corrected *p*-values for multiple tests (16 measures from all reading-related tasks) at $p < .0031$ were also reported.

3.3.2. Multisensory integration task

First, to evaluate whether participants' RTs differed between task conditions, median RTs were analyzed using a 3x2x2 (condition, group, sex) repeated measures ANOVA. Then, to assess the effect of multisensory integration, Miller's RMI (Miller, 1982) was employed. The RMI was analyzed following the step-by-step instructions outlined by Mahoney & Verghese (2019). In brief, at the individual level, all RTs slower than 1000 ms, as well as omitted trials, were set to infinity instead of being excluded from the analysis. Then, to assess violations of the race model, the cumulative probability (CP) for RTs in the multisensory condition was compared to the CP for RTs in unisensory conditions in each range of RTs (percentile bins calculated in 5% increments from the fastest to the slowest responses). The upper limit of CP in the multisensory condition was placed based on the CP from the unisensory conditions, and the race model was considered violated when the CP from the multisensory condition exceeded the CP from the sum of the unisensory conditions (Miller, 1982).

Therefore, at the group level, differences between the CP values predicted by the unisensory conditions and the actual CP values in the multisensory condition were averaged for the whole sample of 88 participants. The group-averaged difference wave was visually inspected to identify violated bins of RTs (i.e., positive values). Then, to assess whether there was a statistically significant violation of the race model across the identified range of RTs, the RMI permutation test with a kill-the-twin correction (which accounts for responses in catch trials to improve statistical power) was employed (Inequality 8 R script provided by Gondan & Minakata, 2016). Finally, for each participant, the area-under-the-curve (AUC) was calculated for the previously determined violated bins of RTs established for the entire dataset. The AUC was used as a measure of multisensory integration, with higher values indicating a greater magnitude of integration. Differences in AUC were analyzed using a 2x2 (group, sex) ANCOVA with age as a covariate, since age was correlated with multisensory integration.

Due to a technical error, one participant (a male from the control group) did not complete all task trials, and his logfiles were not recorded. Despite this, as he completed the great majority of the trials (98 visual-alone, 100 auditory-alone, and 103 multisensory trials), his data were included in the analyses. Behavioral data were retrieved from the EEG file based on the event markers' timings recorded in the signal. In the analysis of the RMI, responses in all missing trials were set to infinity.

3.3.3. EEG data

The EEG signal was processed using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). The data were filtered between 1.6 and 45 Hz using a FIR filter, with a transition bandwidth of 1.6 Hz and cutoff frequencies at (-6dB) [0.8, 45.8] Hz. The high-pass filter was set at 1.6 Hz, following prior ERP research on multisensory integration (e.g., McCracken et al., 2019; Molholm et al., 2020), to prevent pre-stimulus slow anticipatory waves from appearing twice in the SUM (visual-alone + auditory-alone) condition (Teder-Sälejärvi et al., 2002). The EEG signal was then re-referenced to the average of both ear electrodes. Data segments recorded during breaks between blocks and bad channels were manually deleted. The number of deleted channels varied from 0 to 4 (*M* = 0.33, *SD* = 0.78). Then, independent component analysis (ICA) was performed to reject artifacts from the signal. ICLabel (Pion-Tonachini et al., 2019) was used to automatically label components, and those identified as eye blinks, muscle activity, and channel noise were removed.

Epochs were created for each condition (visual-alone, auditory-alone, multisensory) between -100 ms to 500 ms relative to stimulus onset. Next, an automatic rejection criterion of ±100 µV was applied to exclude epochs with excessive amplitudes. Trials with omitted responses and RTs slower than 1000 ms were also excluded. The number of epochs retained for analysis ranged from 53 to 128 (*M* = 113.45, *SD* = 17.90) for the visual-alone condition, 32 to 128 (*M* = 109.65, *SD* = 24.30) for the auditory-alone condition, and 34 to 128 (*M* = 110.98, *SD* = 22.71) for the multisensory condition. A 3x2x2 (condition, group, sex) repeated measures ANOVA revealed a significant effect of condition ($F(1.65, 138.44) = 10.72$, $p < .001$, $\eta^2_p = .113$, Greenhouse-Geisser corrected), with higher number of epochs retained for the analysis in the visual-alone condition compared to both auditory-alone ($p_{\text{corrected}} < .001$) and multisensory condition ($p_{\text{corrected}} = .011$), while the difference between auditory-alone and multisensory condition was not significant ($p_{\text{corrected}} = .134$). Moreover, there was a significant interaction between condition and sex ($F(1.65, 138.44) = 5.40$, $p = .009$, $\eta^2_p = .060$, Greenhouse-Geisser corrected). Post-hoc comparisons revealed that in females there was a higher number of epochs retained for the analysis in the visual-alone condition (*M* = 111.61, *SD* = 20.65) compared to both auditory-alone (*M* = 106.07, *SD* = 27.68, $p_{\text{corrected}} < .001$) and multisensory condition (*M* = 106.43, *SD* = 27.14, $p_{\text{corrected}} < .001$), while in males there was a higher number of epochs retained for the analysis in the multisensory (*M* = 115.52, *SD* = 16.27) than in the auditory-alone condition (*M* = 113.23, *SD* = 20.05, $p_{\text{corrected}} = .044$). Any other comparisons were not significant. Also, the effects of group, sex any other interactions were not significant. Previously deleted channels were interpolated using the nearest neighbor spline method (Perrin et al., 1987, 1989).

ERPs were computed by averaging epochs in each condition (visual-alone, auditory-alone, multisensory), and the SUM condition was generated by adding ERPs from the visual-alone and auditory-alone conditions. The difference wave between multisensory and the SUM condition (multisensory – SUM), was also computed. Comparison between multisensory and SUM conditions is a common approach in ERP research on multisensory integration (e.g., Brandwein et al., 2011; McCracken et al., 2019; Molholm et al., 2020; Teder-Sälejärvi et al., 2002) and relies on the principle of linear summation of electrical fields. Therefore, any discrepancy in neural responses between multisensory and SUM conditions suggests different processing when the stimuli are presented simultaneously or individually.

Next, the Global Field Power (GFP) was computed for the grand average of all conditions (visual-alone, auditory-alone, and multisensory) to determine reliable time windows for analysis. GFP quantifies the spatial standard deviation of the scalp potential across electrodes. A local maximum in the GFP corresponds to a specific distribution of electrical activity on the scalp (a microstate), and a pass between maxima indicates a reorganization of this pattern. Hence, the timing of GFP peaks correspond to the latencies of evoked potentials (Skrandies, 1990). For each time window determined from the GFP, a region with the highest average amplitude across all conditions (visual-alone, auditory-alone, and multisensory) was identified. Then, differences between conditions in the established regions were examined. For each time window, the AUC and the 50% fractional area latency were calculated separately for visual-alone, auditory-alone, multisensory, and SUM conditions. Additionally, the AUC was also calculated for the difference wave (multisensory – SUM). The ERPs were quantified using the AUC instead of the mean amplitude, as it allows to find the area specifically for either positive or negative regions, preventing the cancellation of positive and negative effects each other out in broad measurement windows (Lopez-Calderon & Luck, 2014).

For certain participants, the algorithm failed to identify the specific component within a given time window (typically the P1 component in unisensory conditions), making it impossible to calculate the 50% fractional area latency. This is reflected by a lower number of degrees of freedom in the reported analyses.

First, analyses were performed for the visual-alone and auditory-alone conditions. Separate 2x2 (group, sex) univariate ANOVAs were conducted for the AUC and the 50% fractional area latency of the P1 component (positive area specified). For the N1 and N2 components, separate 2x2x2 (group, sex, hemisphere) repeated measures ANOVAs were conducted for the AUC and the 50% fractional area latency (negative area specified).

Next, to analyze ERPs in the multisensory and SUM conditions, separate 2x2x2 (group, sex, condition) repeated measures ANOVAs were performed for the AUC and 50% fractional area latency for the P1 component, and separate 2x2x2x2 (group, sex, condition, hemisphere) repeated measures ANOVA for the AUC and 50% fractional area latency for the N1 and N2 components. Additionally, a univariate 2x2 (group, sex) ANOVA for the P1 component and separate 2x2x2 (group, sex, hemisphere) repeated measures ANOVAs for the N1 and N2 components were conducted for the AUC of the difference wave (multisensory – SUM).

4. MULTISENSORY INTEGRATION – RESULTS

4.1. Behavioral results

4.1.1. Reading and reading-related tasks

In most reading and reading-related tasks, a significant effect of group indicated that the dyslexic group performed worse than the control group (see Table 2). The only exception was the visual attention test. In this task, participants with dyslexia scored lower than the controls only in the perception speed score, while no significant differences were observed in the number of errors (perceptual discrimination score) or the number of omissions (selective attention score). The effect sizes were large ($\eta^2_p \geq 0.14$) for reading tasks (words and pseudowords read per minute, as well as text reading time in the reading comprehension task), phonological tasks (phoneme deletion and spoonerism tasks), short-term and working memory tasks (digits forward and backward), the orthographic awareness task, and the digits subtest of the RAN task. In turn, the effect sizes were medium ($\eta^2_p \geq 0.06$) for the objects, colors, and letter subtests of the RAN task, as well as for the perception speed score.

Furthermore, a significant effect of sex in the orthographic awareness task ($F(1,84) = 6.06$, $p = .016$, $\eta^2_p = .067$) indicated that females ($M = 0.47$, $SD = 0.17$) performed better than males ($M = 0.40$, $SD = 0.16$). However, this difference was not significant after Bonferroni correction (Table 2). The interaction between group and sex was not significant in any task.

Table 2. *Behavioral results from reading and reading-related tasks (n = 88). For all comparisons, F statistics, p-values (in brackets), and the partial eta squared* (η^2_p) *are provided.*

	DYS F (*n* = 22)		CON F (*n* = 22)		DYS M (*n* = 22)		CON M (*n* = 22)		group *F*(1,84)	η^2_p	sex *F*(1,84)	η^2_p	group*sex *F*(1,84)	η^2_p
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*						
words/min	103.36	23.24	137.32	13.43	107.45	18.48	131.14	12.37	60.16 (< **.001)***	.417	0.08 (.779)	.001	1.91 (.171)	.022
pseudowords/min	54.14	13.48	86.64	19.28	56.45	15.87	79.14	16.99	61.23 (< **.001)***	.422	0.54 (.465)	.006	1.94 (.168)	.023
RAN objects (s)	32.00	4.62	28.36	4.88	33.14	5.84	30.14	4.40	9.83 (**.002**)*	.105	1.89 (.173)	.022	0.09 (.764)	.001
RAN colors (s)	36.73	7.70	30.45	5.05	36.91	7.09	33.73	6.15	11.37 (**.001**)*	.119	1.52 (.221)	.018	1.22 (.273)	.014
RAN digits (s)	20.77	4.11	17.05	3.47	19.64	5.18	16.55	2.22	16.87 (< **.001**)*	.167	0.97 (.327)	.011	0.15 (.702)	.002
RAN letters (s)	23.00	4.12	19.64	3.17	23.45	5.36	20.59	3.02	13.16 (< **.001**)*	.135	0.67 (.414)	.008	0.09 (.772)	.001
reading comprehension (s)	67.05	24.94	40.18	8.57	65.50	18.49	48.32	9.47	37.87 (< **.001**)*	.311	0.85 (.360)	.010	1.83 (.180)	.021
phoneme deletion (% correct)	73.08	25.90	93.88	5.52	75.52	27.49	89.51	13.17	16.33 (< **.001**)*	.163	0.05 (.824)	.001	0.63 (.431)	.007

	DYS F (*n* = 22)		CON F (*n* = 22)		DYS M (*n* = 22)		CON M (*n* = 22)							
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	group *F*(1,84)	η^2_p	sex *F*(1,84)	η^2_p	group*sex *F*(1,84)	η^2_p
spoonerisms phonemes (% correct)	48.05	37.42	84.42	19.30	50.00	35.48	76.30	27.30	22.87 (< **.001**)*	.214	0.22 (.639)	.003	0.59 (.445)	.007
spoonerisms syllables (% correct)	50.76	30.64	73.48	27.05	40.15	29.39	71.21	23.11	20.75 (< **.001**)*	.198	1.19 (.279)	.014	0.50 (.482)	.006
orthographic awareness (accuracy/time)	0.35	0.13	0.58	0.13	0.32	0.13	0.48	0.14	47.01 (< **.001**)*	.359	6.06 (**.016**)	.067	1.48 (.227)	.017
perception speed (sten score)	3.32	2.21	4.73	1.91	2.82	1.76	3.95	1.29	10.72 (**.002**)*	.113	2.68 (.105)	.031	0.12 (.727)	.001
perceptual discrimination (percentile score)	90.91	19.41	95.05	0.21	90.91	19.41	95.05	0.21	2.00 (.161)	.023	0.00 (1.00)	.000	0.00 (1.00)	.000
selective attention (quartile score)	2.00	0.98	2.09	1.02	1.95	0.95	2.00	1.02	0.10 (.748)	.001	0.10 (.748)	.001	0.01 (.915)	.000
digits forward	5.45	1.87	6.55	1.90	5.27	1.67	7.27	2.23	14.16 (< **.001**)*	.144	0.44 (.508)	.005	1.23 (.272)	.014
digits backward	5.36	1.84	6.77	1.95	4.77	1.15	7.50	2.16	28.61 (< **.001**)*	.254	0.03 (.860)	.000	2.91 (.092)	.033

Note. CON – control group; DYS – dyslexic group; F – females; M – males; RAN – rapid automatized naming. Boldface indicates statistical significance at $p < .05$ level (uncorrected).
*Significance after Bonferroni correction at $p < .0031$

4.1.2. Multisensory integration task

Regarding median RTs in the task, one participant (a female from the control group) was identified as an outlier due to median RTs exceeding 3 SDs in all conditions. Therefore, she was excluded from this analysis. A 3x2x2 (condition, group, sex) repeated measures ANOVA revealed a significant main effect of condition ($F(1.69, 140.14) = 198.41$, $p < .001$, $\eta^2_p = .705$, Greenhouse-Geisser corrected). Post-hoc comparisons indicated that RTs in the multisensory condition ($M = 239.03$, $SD = 37.70$) were faster than those in both the auditory ($M = 269.62$, $SD = 50.25$, $p_{\text{corrrected}} < .001$) and visual ($M = 281.02$, $SD = 42.22$, $p_{\text{corrrected}} < .001$) conditions. Additionally, RTs in the auditory condition were faster than those in the visual condition ($p_{\text{corrrected}} < .001$). The effects of group, sex, and any interactions were not significant. Boxplots illustrating median RTs from the task are presented in Figure 4.

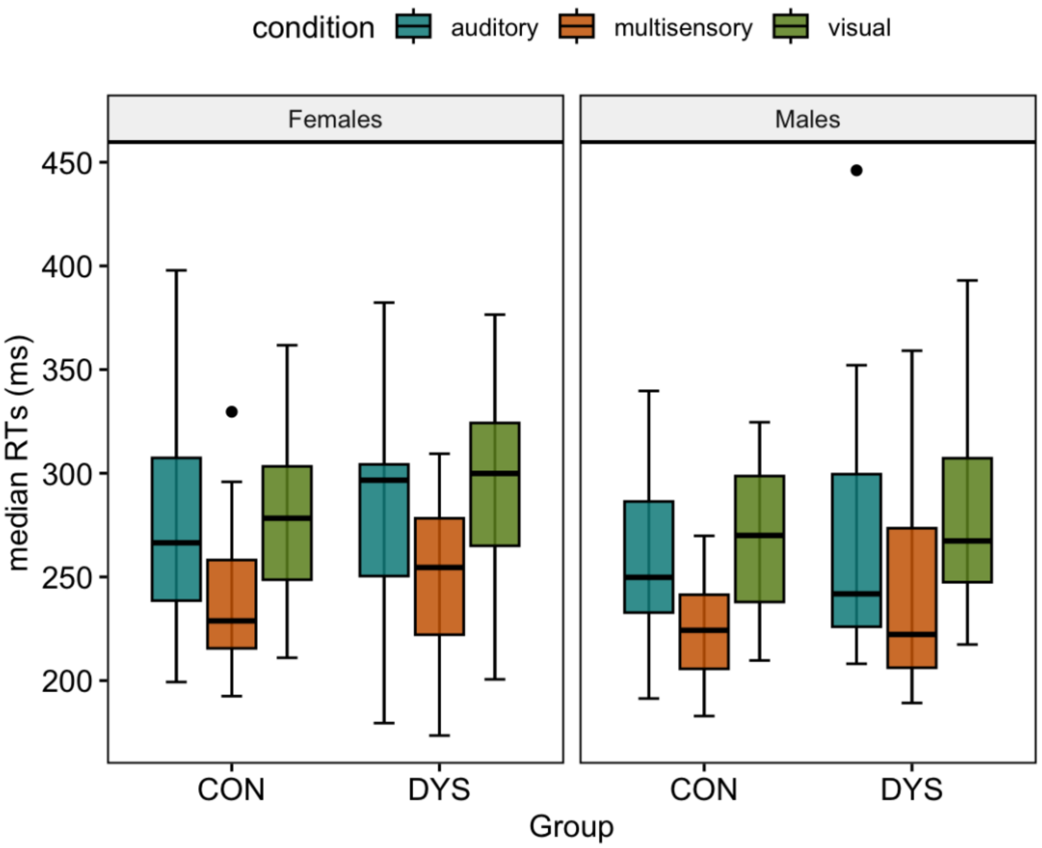

Figure 4. *Boxplots showing median reaction times (RTs) in the redundant-target effect task separately for females and males from the control (CON) and dyslexic (DYS) groups.*

For the RMI, data from all participants were included since the RMI does not rely on median RTs. All participants had an accuracy rate above 70% in every condition, so no one was excluded based on high omission rates (Mahoney & Verghese, 2019).

Across the entire sample of 88 participants, the race model was violated within the first four quantiles (15%) of the RTs distribution (see Figure 5), and this violation was significant (*p* < .001) as determined by the RMI permutation test with the kill-the-twin correction (Inequality 8 R script; Gondan & Minakata, 2016).

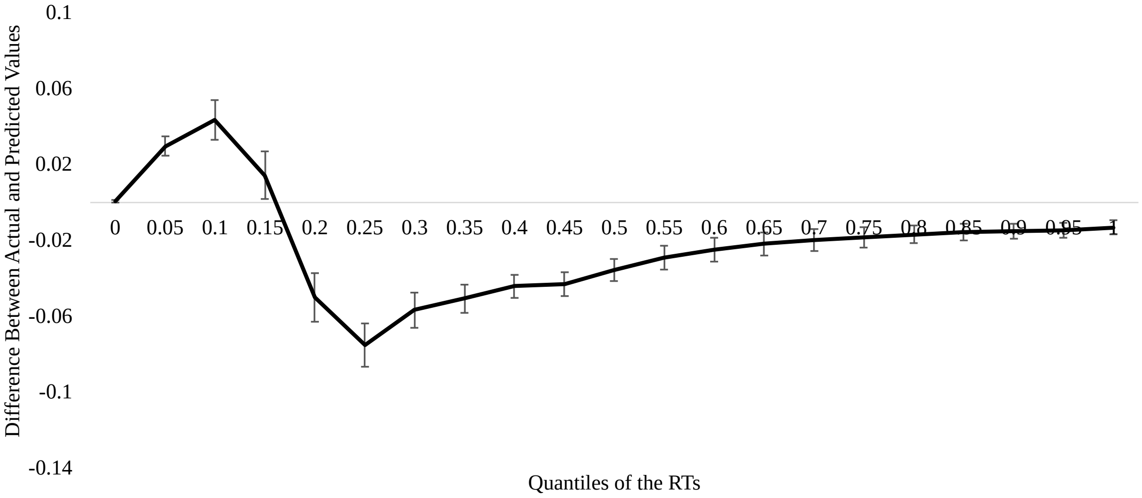

Figure 5. *Race model difference wave between actual and predicted values in the whole sample (n = 88). The race model was violated within the first four quantiles (15%) of the reaction times (RTs). Bars represent the standard error of the mean.*

Next, to analyze differences in magnitude of multisensory integration, for each participant the AUC was calculated for the first four quantiles (15%) of RTs. Since age was found to be positively correlated with AUC (*r* = .38, *p* < .001), a univariate 2x2 (group, sex) ANCOVA with age as a covariate was employed. The results indicated significant effects of age (*F*(1,83) = 15.75, *p* < .001, η^2_p = .159) and group (*F*(1,83) = 4.46, *p* = .038, η^2_p = .051), indicating a lower magnitude of multisensory integration in the dyslexic (*M* = 0.04, *SD* = 0.16) compared to the control group (*M* = 0.12, *SD* = 0.17). Additionally, there was a significant interaction between group and sex (*F*(1,83) = 4.55, *p* = .036, η^2_p = .052). Post-hoc comparisons revealed that males in the dyslexic group had a lower magnitude of multisensory integration (*M* = -0.01, *SD* = 0.11) compared to males in the control group (*M* = 0.13, *SD* = 0.22, $p_{\text{corrrected}}$ = .004). However, the difference between females in the dyslexic (*M* = 0.10, *SD* = 0.19) and control (*M* = 0.10, *SD* = 0.12) groups was not significant ($p_{\text{corrrected}}$ = .989). Furthermore, there was a significant difference between females and males within the dyslexic group ($p_{\text{corrrected}}$ = .020), but not within the control group ($p_{\text{corrrected}}$ = .525) indicating that the reduced magnitude of multisensory integration observed among dyslexic males, compared to dyslexic females, cannot be explained by control males outperforming control females. Differences between actual and predicted values separately for females and males are presented in Figure 6.

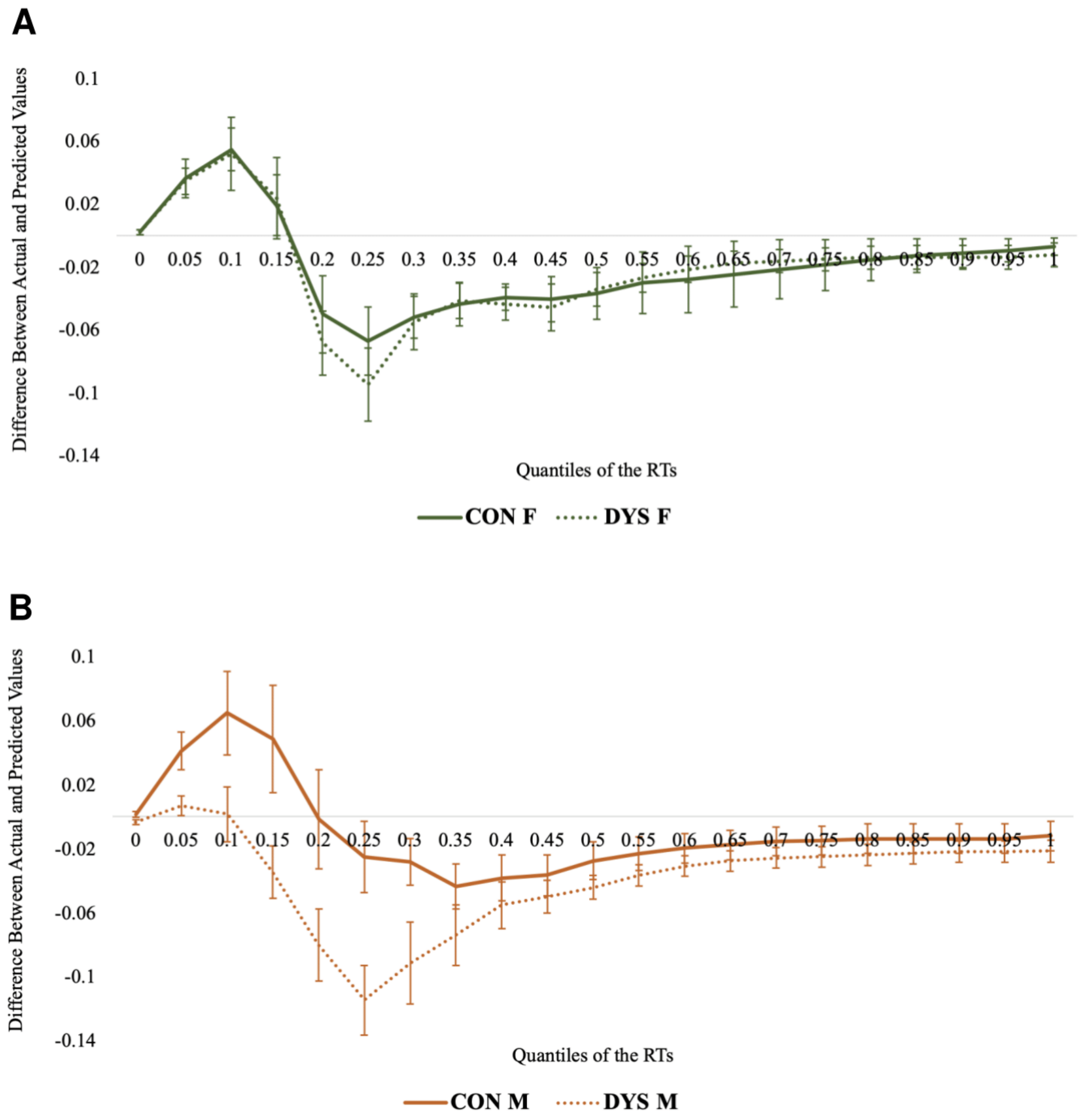

Figure 6. *Race model difference wave between actual and predicted values separately for* ***(A)*** *females and* ***(B)*** *males from the control (CON) and dyslexic (DYS) groups. Bars represent the standard error of the mean.*

4.2. EEG results

Based on the GFP (Figure 7), three time-windows were selected – 56-82 ms, 98-196 ms, and 196-384 ms. For each time window, specific electrodes were chosen based on the greatest mean amplitude topography (Figure 7) and averaged for the analyses.

For the 56-82 ms window (P1 component), three central electrodes (FC1, FCz, FC2) were selected. For the 98-196 ms window (N1 component), eight electrodes in the left hemisphere (F5, FC5, FC3, FC1, C3, C5, CP1, CP5) and the corresponding eight electrodes in the right hemisphere (F6, FC6, FC4, FC2, C4, C6, CP2, CP6) were chosen. For the 196-384 ms window (N2 component), six electrodes in the left hemisphere (AF7, AF3, F7, F5, F3, F1) and the corresponding six in the right hemisphere (AF8, AF4, F8, F6, F4, F2) were selected.

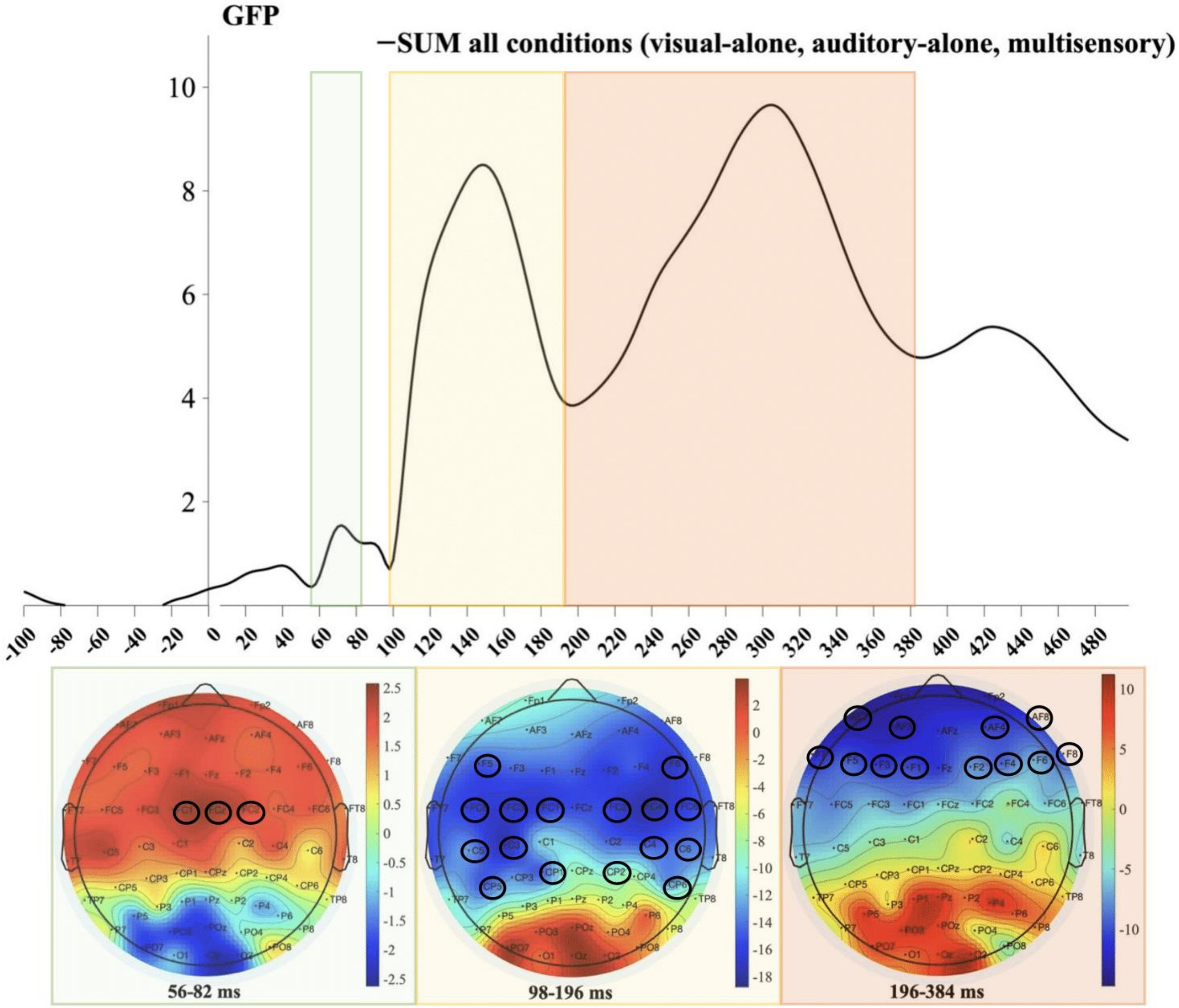

Figure 7. *Global field power (GFP) and mean amplitude topographies in three time windows selected from the GFP for the sum of all conditions in the whole sample (n = 88). The electrodes selected for the analyses are marked in black.*

4.2.1. Visual-alone condition

56-82 ms (P1 Component)

No significant effects or interactions either for AUC or 50% fractional area latency were found.

98-196 ms (N1 Component)

For the AUC there were no significant effects or interactions. However, for the 50% fractional area latency, a significant effect of sex was found ($F(1,84) = 5.25, p = .024, \eta^2_p = .059$), with the N1 component occurring later in males ($M = 150.77$, $SD = 11.92$) compared to females ($M = 145.12$, $SD = 11.17$). No other effects or interactions were significant.

196-384 ms (N2 Component)

For the AUC, a significant effect of hemisphere was found ($F(1,84) = 12.76$, $p < .001$, $\eta^2_p = .132$) with greater AUC in the left ($M = 0.90$, $SD = 0.83$) compared to the right hemisphere ($M = 0.84$, $SD = 0.74$). No other effects or interactions were significant.

For the 50% fractional area latency, a significant effect of hemisphere was found ($F(1,82) = 16.13$, $p < .001$, $\eta^2_p = .164$) with the N2 component occurring later in the left ($M = 291.36$, $SD = 22.60$) than in the right hemisphere ($M = 286.55$, $SD = 23.29$). Also, there was a significant effect of group ($F(1,82) = 4.96$, $p = .029$, $\eta^2_p = .057$) with the N2 component occurring later in the dyslexic ($M = 294.24$, $SD = 22.79$) than in the control group ($M = 283.68$, $SD = 20.68$). No other effects or interactions were significant.

4.2.2. Auditory-alone condition

56-82 ms (P1 Component)

For the AUC there were no significant effects or interactions. However, for the 50% fractional area latency, a significant effect of sex was found ($F(1,76) = 5.54, p = .021$, $\eta^2_p = .068$) with the P1 component occurring later in males ($M = 69.88$, $SD = 4.95$) compared to females ($M = 67.32$, $SD = 5.06$). No other effects or interactions were significant.

98-196 ms (N1 Component)

For the AUC there were no significant effects or interactions. For the 50% fractional area latency, a significant effect of hemisphere was found ($F(1,84) = 4.35$, $p = .040$, $\eta^2_p = .049$) with the N1 component occurring later in the left ($M = 144.42$, $SD = 10.63$) than in the right hemisphere ($M = 142.97$, $SD = 9.86$). No other effects or interactions were significant.

196-384 ms (N2 Component)

For the AUC, a significant effect of hemisphere was found ($F(1,84) = 22.90$, $p < .001$, $\eta^2_p = .214$) with greater AUC in the left ($M = 0.50$, $SD = 0.38$) than in the right hemisphere ($M = 0.42$, $SD = 0.31$). No other effects or interactions were significant. For the 50% fractional area latency no significant effects or interactions were found.

4.2.3. Multisensory and SUM (visual-alone + auditory-alone) conditions

Separate ERPs for multisensory and SUM conditions for the dyslexic and control groups in four selected electrodes (F5, F6, FC1, FC2) are presented in Figure 8A.

56-82 ms (P1 Component)

For the AUC, a significant effect of condition was found ($F(1,84) = 4.64$, $p = .034$, $\eta^2_p = .052$) with greater AUC in the SUM ($M = 0.05$, $SD = 0.04$) than in the multisensory condition ($M = 0.04$, $SD = 0.03$). No other effects or interactions were significant. For the AUC of the difference wave (multisensory – SUM) there were no significant effects or interactions.

For the 50% fractional area latency a significant effect of condition was found ($F(1,73) = 22.83$, $p < .001$, $\eta^2_p = .238$) with the P1 component occurring later in the SUM ($M = 70.87$, $SD = 4.95$) than in the multisensory condition ($M = 67.85$, $SD = 4.80$). No other effects or interactions were significant.

98-196 ms (N1 Component)

For the AUC, a significant effect of condition was found ($F(1,84) = 43.27$, $p < .001$, $\eta^2_p = .340$) with greater AUC in the SUM ($M = 0.84$, $SD = 0.33$) than in the multisensory condition ($M = 0.75$, $SD = 0.30$), the effect of sex ($F(1,84) = 6.88$, $p = .010$, $\eta^2_p = .076$) with greater AUC in females ($M = 0.88$, $SD = 0.31$) than in males ($M = 0.71$, $SD = 0.29$) and an interaction between group and condition ($F(1,84) = 8.31$, $p = .005$, $\eta^2_p = .090$). Post-hoc comparisons indicated that the greater AUC in the SUM than in the multisensory condition was significant both in the dyslexic ($M_{SUM} = 0.80$, $SD_{SUM} = 0.35$, $M_{multisensory} = 0.75$, $SD_{multisensory} = 0.35$, $p_{\text{corrrected}} = .011$) and the control group ($M_{SUM} = 0.88$, $SD_{SUM} = 0.32$. $M_{multisensory} = 0.75$, $SD_{multisensory} = 0.25$, $p_{\text{corrrected}} < .001$). However, the difference between groups was not significant either in the multisensory ($p_{\text{corrrected}} = .980$) or SUM conditions ($p_{\text{corrrected}} = .260$).

For the AUC of the difference wave (multisensory – SUM) a significant effect of group was found ($F(1,84) = 5.99$, $p = .016$, $\eta^2_p = .067$) with a greater difference between multisensory and SUM conditions in the control (*M* = 0.21, *SD* = 0.12) compared to the dyslexic group (*M* = 0.15, *SD* = 0.08). No other effects or interactions were significant.

For the 50% fractional area latency, a significant effect of condition was found ($F(1,84) = 9.50$, $p = .003$, $\eta^2_p = .102$) with the N1 component occurring later in the multisensory (*M* = 147.02, *SD* = 9.43) than in the SUM condition (*M* = 145.20, *SD* = 8.76) and the effect of sex ($F(1,84) = 8.36$, $p = .005$, $\eta^2_p = .090$) with the N1 component occurring later in males (*M* = 148.69, *SD* = 9.17) than in females (*M* = 143.54, *SD* = 7.42). No other effects or interactions were significant.

196-384 ms (N2 Component)

For the AUC, a significant effect of condition was found ($F(1,84) = 18.15$, $p < .001$, $\eta^2_p = .178$) with greater AUC in the SUM (*M* = 1.23, *SD* = 1.02) than in the multisensory condition (*M* = 1.08, *SD* = 0.92), the effect of hemisphere ($F(1,84) = 36.18$, $p < .001$, $\eta^2_p = .301$) with greater AUC in the left (*M* = 1.25, *SD* = 1.06) than in the right hemisphere (*M* = 1.06, *SD* = 0.86) and interactions between hemisphere and condition ($F(1,84) = 5.67$, $p = .019$, $\eta^2_p = .063$) and between group and condition ($F(1,84) = 6.26$, $p = .014$, $\eta^2_p = .069$). For the hemisphere*condition interaction, post-hoc comparisons indicated that the greater AUC in the SUM than in the multisensory condition was found both in the left ($M_{SUM} = 1.32$, $SD_{SUM} = 1.12$, $M_{multisensory} = 1.19$, $SD_{multisensory} = 1.04$, $p_{\text{corrrected}} < .001$) and right hemispheres ($M_{SUM} = 1.15$, $SD_{SUM} = 0.93$, $M_{multisensory} = 0.97$, $SD_{multisensory} = 0.82$, $p_{\text{corrrected}} < .001$). Also, a greater AUC for both SUM and multisensory conditions was found in the left compared to the right hemisphere ($p_{\text{corrrected}} < .001$). For the group*condition interaction, post-hoc comparisons indicated that the greater AUC for the SUM (*M* = 1.34, *SD* = 1.09) compared to the multisensory condition (*M* = 1.09, *SD* = 0.97, $p_{\text{corrrected}} < .001$) was significant in the control group, while not in the dyslexic group ($M_{SUM} = 1.13$, $SD_{SUM} = 0.94$, $M_{multisensory} = 1.07$, $SD_{multisensory} = 0.88$, $p_{\text{corrrected}} = .217$). However, the difference between groups was not significant either in the multisensory ($p_{\text{corrrected}} = .897$) or SUM conditions ($p_{\text{corrrected}} = .350$).

For the AUC of the difference wave (multisensory – SUM) a significant effect of hemisphere was found ($F(1,84) = 5.75$, $p = .019$, $\eta^2_p = .064$) with a greater difference between multisensory and SUM conditions in the right (*M* = 0.37, *SD* = 0.27) than in the left hemisphere (*M* = 0.34, *SD* = 0.25) and the effect of group ($F(1,84) = 5.80$, $p = .018$, $\eta^2_p = .065$) with a greater difference in the control (*M* = 0.42, *SD* = 0.29) compared to the dyslexic group (*M* = 0.29, *SD* = 0.20). Violin plots illustrating results for the difference wave in N1 and N2 components separately for dyslexic and control groups are presented in Figure 8B. No other effects or interactions were significant.

For the 50% fractional area latency, a significant effect of group was found ($F(1,84) = 5.85$, $p = .018$, $\eta^2_p = .065$) with the N2 component occurring later in the dyslexic ($M = 294.44$, $SD = 21.47$) than in the control group ($M = 284.12$, $SD = 18.40$) and an interaction between condition, hemisphere, and sex ($F(1,84) = 4.28$, $p = .042$, $\eta^2_p = .048$). However, no significant differences were revealed by post-hoc comparisons for this interaction. No other effects or interactions were significant.

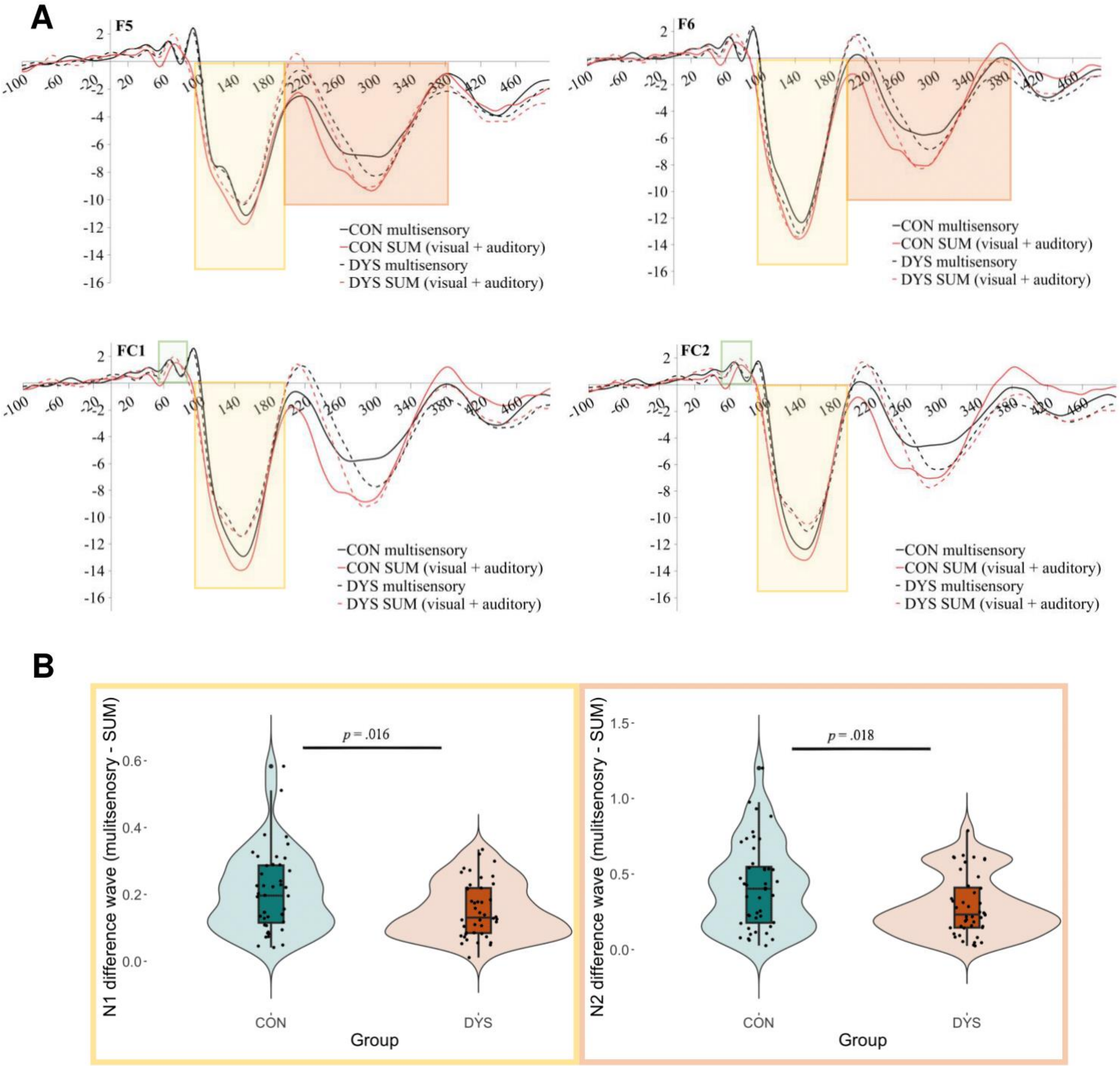

Figure 8. *(A) ERPs for multisensory and SUM conditions in four selected electrodes in left (F5, FC1) and right (F6, FC2) hemispheres.* ***(B)*** *Violin plots illustrating difference between conditions in N1 and N2 components separately for the control (CON) and dyslexic (DYS) groups (n = 88).*

4.3. Relationships between reading and multisensory integration

Next, correlations between reading speed and behavioral and neural indices of multisensory integration were evaluated. Number of pseudowords read per minute was used as the measure of reading speed due to its the most consistent ability to predict reading difficulties in adults (Brèthes et al., 2022; Carioti et al., 2021; Reis et al., 2020). To reduce the number of correlations, values obtained from the left and right hemispheres in N1 and N2 components were averaged. Two-tailed correlations were performed in the whole sample (Table 3) followed by one-tailed correlations performed separately for females and males (Table 4) to validate relationships obtained in the entire sample separately for each sex. One-tailed statistics were employed in separate correlations for females and males, since the directions of the correlations had been already established through the two-tailed correlations on the whole sample. Non-parametric Spearman's correlations were conducted due to violations of the normal distribution. Correlation matrices were presented with both uncorrected *p*-values and Bonferroni corrected values adjusted for 9 planned comparisons between reading speed and the behavioral and neural indices of multisensory integration at $p < .0056$.

Table 3. *Spearman's correlations between reading speed and behavioral and neural indices of multisensory integration in the whole sample (n = 88).*

Variable	1.	2.	3.	4.	5.	6.
1. pseudowords/min	–					
2. magnitude of multisensory integration	.22*	–				
3. N1 AUC difference wave	.21	.14	–			
4. N1 50% FAL multisensory	-.07	-.22*	-.09	–		
5. N2 AUC difference wave	.12	-.10	.24*	.17	–	
6. N2 50% FAL multisensory	-.31**	-.18	.-.28*	-.00	-.22*	–

Note. AUC – area-under-the-curve; 50% FAL – 50% fractional area latency.
**p < .01 (two-tailed uncorrected); *p < .05 (two-tailed uncorrected).
Underscore indicates significance after Bonferroni correction at $p < .0056$

In the whole sample, the magnitude of multisensory integration was positively correlated with number of pseudowords read in one minute (r(86) = .22, $p = .040$) and negatively with 50% fractional area latency in the N1 component in the multisensory condition (r(86) = -.22, *p* = .041). Moreover, the latency of the N2 component in the multisensory condition was negatively correlated with number of pseudowords read in one minute (r(86) = -.31, *p* = .004). However, the only significant result after Bonferroni correction, was the negative correlation between N2 latency and number of pseudowords read in one minute (Table 3).

In females only, the magnitude of multisensory integration was negatively correlated with the AUC in the difference wave in the N2 component (r(42) = -.25, *p* = .050). Additionally, the 50% fractional area latency in the N2 component in the multisensory condition was negatively correlated with number of pseudowords read in one minute (r(42) = -.41, *p* = .003), and this correlation was significant after Bonferroni correction (Table 4).

In males only, the magnitude of multisensory integration was positively correlated with number of pseudowords read in one minute (r(42) = .29, *p* = .027) and negatively with the 50% fractional area latency in the N2 component in the multisensory condition (r(42) = -.29, *p* = .029). Furthermore, the AUC in the difference wave in the N1 component was positively correlated with number of pseudowords read in one minute (r(42) = .33, *p* = .015). Nevertheless, none of these relationships was significant after Bonferroni correction (Table 4).

Table 4. *Spearman's correlations between reading speed and behavioral and neural indices of multisensory integration separately for females and males (n = 88).*

	Females (*n* = 44)						**Males (*n* = 44)**					
Variable	1.	2.	3.	4.	5.	6.	1.	2.	3.	4.	5.	6.
1. pseudowords/min	–						–					
2. magnitude of multisensory integration	.12	–					.29*	–				
3. N1 AUC difference wave	.11	.21	–				.33*	.07	–			
4. N1 50% FAL multisensory	.02	-.24	-.06	–			-.09	-.11	-.01	–		
5. N2 AUC difference wave	.22	-.25*	.17	.10	–		.10	.04	.34*	.23	–	
6. N2 50% FAL multisensory	-.41**	-.11	-.31*	.03	-.21	–	-.17	-.29*	-.32*	.07	-.22	–

Note. AUC – area-under-the-curve; 50% FAL – 50% fractional area latency.
***p* < .01 (one-tailed uncorrected); **p* < .05 (one-tailed uncorrected).
Underscore indicates significance after Bonferroni correction at *p* < .0056

4.4. Results for a subsample of 80 participants (out of 88) matched in nonverbal IQ

Since in the entire sample of 88 participants, dyslexic and control groups differed in the nonverbal subscale of IQ, I conducted a repetition of all analyses on a subsample of 80 participants matched for nonverbal IQ.

4.4.1. Participants

Alike the entire sample of 88 participants, dyslexic and control groups were matched in terms of age, sex and family socio-economic status. Additionally, groups were matched for nonverbal IQ (see Table 5).

4.4.2. Behavioral results

4.4.2.1. Reading and reading-related tasks

Similar to the results from the entire sample, the dyslexic group performed worse than the control group in most reading and reading-related tasks, except for perceptual discrimination and selective attention scores from the visual attention test (see Table 6). However, unlike the analysis of the whole sample of 88 participants, the differences between groups in the RAN subtest of objects and the perception speed score were not significant after applying the Bonferroni correction for multiple comparisons.

Table 5. *Descriptive statistics for demographic characteristics separately for females and males in dyslexic and control groups (n = 80). For all comparisons, F statistics, p-values (in brackets), and the partial eta squared* (η^2_p) *are provided.*

	DYS F (*n* = 20)		CON F (*n* = 20)		DYS M (*n* = 20)		CON M (*n* = 20)		group *F*(1,76)	η^2_p	sex *F*(1,76)	η^2_p	group*sex *F*(1,76)	η^2_p
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*						
Age	19.40	3.58	19.62	3.42	19.65	3.32	19.39	2.89	0.00 (.978)	.000	0.00 (.986)	.000	0.11 (.744)	.001
Mother's education (years)	16.70	3.05	16.18	2.52	17.28	4.20	17.05	2.11	0.30 (.587)	.004	1.11 (.295)	.014	0.05 (.828)	.001
Father's education (years)	16.05	3.32	16.60	3.79	16.60	2.76	16.63[a]	3.13[a]	0.16[c] (.694)	.002	0.16[c] (.694)	.002	0.12[c] (.726)	.002
IQ	106.00	11.70	108.35	9.21	103.47[b]	10.18[b]	111.60	8.83	5.37[c] (**.023**)	.067	0.03[c] (.873)	.000	1.63[c] (.205)	.021
Nonverbal IQ (scaled score)	10.65	2.87	10.55	2.52	10.55	2.70	11.95	2.16	1.27 (.263)	.016	1.27 (.263)	.016	1.69 (.197)	.022
ARHQ-PL	53.00	8.71	24.75	5.68	50.35	12.15	25.05	9.84	162.71 (**< .001**)	.682	0.31 (.577)	.004	0.49 (.484)	.006

Note. CON – control group; DYS – dyslexic group; F – females; M – males; ARHQ-PL – Polish version of the Adult Reading History Questionnaire.
Boldface indicates statistical significance at $p < .05$ level (uncorrected).

[a] $n = 19$ (one participant did not provide information about the father's education);

[b] $n = 19$ (one participant did not attempt a verbal subtest of the scale, thus his overall IQ could not be calculated);

[c] $F(1,75)$

Table 6. *Behavioral results from reading and reading-related tasks (n = 80). For all comparisons, F statistics, p-values (in brackets), and the partial eta squared* (η^2_p) *are provided.*

	DYS F (*n* = 20)		CON F (*n* = 20)		DYS M (*n* = 20)		CON M (*n* = 20)		group *F*(1,76)	η^2_p	sex *F*(1,76)	η^2_p	group*sex *F*(1,76)	η^2_p
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*						
words/min	103.85	24.09	137.70	13.12	105.25	17.90	131.15	12.60	57.97 (< **.001**)*	.433	0.43 (.514)	.006	1.03 (.314)	.013
pseudowords/min	55.45	13.45	87.45	18.44	54.45	15.16	78.15	17.46	58.77 (< **.001**)*	.436	2.01 (.160)	.026	1.31 (.257)	.017
RAN objects (s)	31.30	3.76	28.10	4.66	33.65	5.89	30.35	4.56	9.26 (**.003**)	.109	4.64 (**.034**)	.058	0.00 (.963)	.000
RAN colors (s)	36.65	8.02	30.05	4.81	37.25	7.36	33.95	6.42	10.73 (**.002**)*	.124	2.22 (.141)	.028	1.19 (.278)	.015
RAN digits (s)	20.75	4.30	16.75	3.45	20.25	5.03	16.65	2.30	18.96 (< **.001**)*	.200	0.12 (.732)	.002	0.05 (.819)	.001
RAN letters (s)	22.70	4.19	19.25	2.69	24.05	5.26	20.35	3.00	16.64 (< **.001**)*	.180	1.95 (.166)	.025	0.02 (.887)	.000
reading comprehension (s)	66.20	25.36	40.00	8.84	66.40	18.76	49.05	9.59	32.55 (< **.001**)*	.300	1.47 (.229)	.019	1.34 (.250)	.017
phoneme deletion (% correct)	77.31	22.56	94.23	5.37	75.58	28.74	88.46	13.38	11.52 (**.001**)*	.132	0.73 (.396)	.010	0.21 (.647)	.003

	DYS F (*n* = 20)		CON F (*n* = 20)		DYS M (*n* = 20)		CON M (*n* = 20)		group *F*(1,76)	η^2_p	sex *F*(1,76)	η^2_p	group*sex *F*(1,76)	η^2_p
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*						
spoonerisms phonemes (% correct)	52.86	35.78	87.50	11.79	50.36	35.79	74.29	27.85	19.74 (< **.001**)*	.206	1.42 (.237)	.018	0.66 (.419)	.009
spoonerisms syllables (% correct)	55.83	27.19	76.67	22.56	38.33	30.16	70.83	24.11	20.78 (< **.001**)*	.215	3.98 (**.050**)	.050	0.99 (.322)	.013
orthographic awareness (accuracy/time)	0.36	0.13	0.58	0.14	0.32	0.13	0.47	0.15	35.52 (< **.001**)*	.319	5.80 (**.018**)	.071	1.21 (.276)	.016
perception speed (sten score)	3.40	2.30	4.85	1.95	2.85	1.84	3.90	1.33	8.74 (**.004**)	.103	3.15 (.080)	.040	0.22 (.638)	.003
perceptual discrimination (percentile score)	90.45	20.35	95.05	0.22	95.05	0.22	95.05	0.22	1.02 (.315)	.013	1.02 (.315)	.013	1.02 (.315)	.013
selective attention (quartile score)	2.05	1.00	2.10	1.02	1.95	1.00	2.00	1.03	0.05 (.826)	.001	0.20 (.660)	.003	0.00 (1.00)	.000
digits forward	5.55	1.88	6.75	1.86	5.15	1.63	7.20	2.31	14.11 (< **.001**)*	.157	0.00 (.954)	.000	0.97 (.329)	.013
digits backward	5.55	1.82	7.05	1.82	4.80	1.11	7.55	2.24	28.12 (< **.001**)*	.270	0.10 (.756)	.001	2.43 (.123)	.031

Note. CON – control group; DYS – dyslexic group; F – females; M – males; RAN – rapid automatized naming. Boldface indicates statistical significance at $p < .05$ level (uncorrected).
*Significance after Bonferroni correction at $p < .0031$

4.4.2.2. Multisensory integration task

All results from the entire sample of 88 participants were replicated. In the analysis of the median RTs in the task, similarly to the analysis on the whole sample, one participant was excluded from this analysis based on median RTs exceeding 3 SDs in all task conditions. A 3x2x2 (condition, group, sex) repeated measures ANOVA indicated a main effect of condition ($F(1.72, 129.03) = 188.64$, $p < .001$, $\eta^2_p = .716$, Greenhouse-Geisser corrected) with RTs in multisensory condition ($M = 238.92$, $SD = 37.08$) being faster than those in auditory ($M = 269.45$, $SD = 49.05$, $p_{\text{corrrected}} < .001$) and in visual conditions ($M = 281.36$, $SD = 41.96$, $p_{\text{corrrected}} < .001$). Moreover, RTs in auditory condition were faster than in those in the visual condition ($p_{\text{corrrected}} < .001$). The effects of group, sex, and any interactions were not significant.

In the analysis of the RMI, a univariate 2x2 (group, sex) ANCOVA with age as a covariate indicated significant effects of age ($F(1,75) = 13.14$, $p < .001$, $\eta^2_p = .149$) and group ($F(1,75) = 3.97$, $p = .050$, $\eta^2_p = .050$) with a lower magnitude of multisensory integration in the dyslexic ($M = 0.05$, $SD = 0.17$) compared to the control group ($M = 0.12$, $SD = 0.18$). Additionally, a significant interaction between group and sex ($F(1,75) = 4.66$, $p = .034$, $\eta^2_p = .059$) indicated that males from the dyslexic group had a lower magnitude of multisensory integration ($M = -0.01$, $SD = 0.12$) than males from the control group ($M = 0.13$, $SD = 0.23$, $p_{\text{corrrected}} = .004$) while difference between females from dyslexic ($M = 0.10$, $SD = 0.20$) and control groups ($M = 0.10$, $SD = 0.12$) were not significant ($p_{\text{corrrected}} = .905$). Furthermore, the difference between females and males was found to be significant only in the dyslexic ($p_{\text{corrrected}} = .022$), and not in the control group ($p_{\text{corrrected}} = .478$).

4.4.3. EEG results

4.4.3.1. Visual-alone condition

56-82 ms (P1 Component)

Alike the results from the entire sample, no significant effects or interactions were observed for either AUC or 50% fractional area latency.

98-196 ms (N1 Component)

Results from the entire sample were replicated. No significant effects or interactions were found for the AUC. For the 50% fractional area latency, a significant effect of sex was found ($F(1,76) = 5.81$, $p = .018$, $\eta^2_p = .071$) with the N1 component occurring later in males (*M* = 151.72, *SD* = 11.93) compared to females (*M* = 145.37, *SD* = 11.54). No other effects or interactions were significant.

196-384 ms (N2 Component)

All results were replicated. For the AUC, a significant effect of hemisphere (*F*(1,76) = 12.70, *p* < .001, η^2_p = .143) indicated that AUC was greater in the left (*M* = 0.90, *SD* = 0.80) than in the right hemisphere (*M* = 0.83, *SD* = 0.72). No other effects or interactions were significant.

For the 50% fractional area latency, a significant effect of hemisphere was found (*F*(1,74) = 12.71, *p* < .001, η^2_p = .147) with the N2 component occurring later in the left (*M* = 289.51, *SD* = 20.82) than in the right hemisphere (*M* = 285.38, *SD* = 20.84) and the effect of group (*F*(1,74) = 7.16, *p* = .009, η^2_p = .088) with the N2 component occurring later in the dyslexic (*M* = 293.41, *SD* = 18.77) compared to the control group (*M* = 281.49, *SD* = 20.02). No other effects or interactions were significant.

4.4.3.2. Auditory-alone condition

56-82 ms (P1 Component)

Results from the entire sample were replicated. No significant effects or interactions were found for the AUC. For the 50% fractional area latency, a significant effect of sex was observed (*F*(1,68) = 7.49, *p* = .008, η^2_p = .099) with the P1 component occurring later in males (*M* = 70.06, *SD* = 5.16) than in females (*M* = 66.85, *SD* = 4.96). No other effects or interactions were significant.

98-196 ms (N1 Component)

In contrast to the analysis on the entire sample, which revealed a significant effect of hemisphere for both AUC and 50% fractional area latency, no significant effects or interactions were found in either measure here.

196-384 ms (N2 Component)

Alike the results from the entire sample, for the AUC, there was a significant effect of hemisphere (*F*(1,76) = 21.09, *p* < .001, η^2_p = .217) indicating that the AUC was greater in the left (*M* = 0.48, *SD* = 0.36) than in the right hemisphere (*M* = 0.41, *SD* = 0.31). No other effects or interactions were significant. For the 50% fractional area latency, no significant effects or interactions were found.

4.4.3.3. Multisensory and SUM (visual-alone + auditory-alone) conditions

56-82 ms (P1 Component)

In contrast to the results obtained from the entire sample, the effect of condition for the AUC was not significant ($F(1,76) = 2.06$, $p = .155$, $\eta^2_p = .026$). However, a significant interaction between group and condition was observed here ($F(1,76) = 5.31$, $p = .024$, $\eta^2_p = .065$), with greater AUC in the SUM condition ($M = 0.05$, $SD = 0.04$) compared to the multisensory condition ($M = 0.03$, $SD = 0.03$, $p_{\text{corrrected}} = .010$) significant in the dyslexic group, while not in the control group ($M_{SUM} = 0.04$, $SD_{SUM} = 0.04$, $M_{multisensory} = 0.04$, $SD_{multisensory} = 0.04$, $p_{\text{corrrected}} = .540$). The difference between groups was not significant either in the multisensory ($p_{\text{corrrected}} = .394$) or SUM conditions ($p_{\text{corrrected}} = .292$). No other effects or interactions were significant. Alike the results from the entire sample, there were no significant effects or interactions for the AUC of the difference wave (multisensory – SUM).

For the 50% fractional area latency, the results from the entire sample replicated. There was a significant effect of condition ($F(1,65) = 16.85$, $p < .001$, $\eta^2_p = .206$) with the P1 component occurring later in the SUM ($M = 70.82$, $SD = 5.14$) compared to the multisensory condition ($M = 67.97$, $SD = 4.92$). No other effects or interactions were significant.

98-196 ms (N1 Component)

For the AUC, all results were replicated. There was a significant effect of condition ($F(1,76) = 38.37$, $p < .001$, $\eta^2_p = .335$) indicating that the AUC was greater in the SUM ($M = 0.83$, $SD = 0.34$) than in the multisensory condition ($M = 0.74$, $SD = 0.31$), the effect of sex ($F(1,76) = 5.78$, $p = .019$, $\eta^2_p = .071$) indicating that the AUC was greater in females ($M = 0.87$, $SD = 0.31$) than in males ($M = 0.70$, $SD = 0.30$) and an interaction between group and condition ($F(1,76) = 6.18$, $p = .015$, $\eta^2_p = .075$). Post-hoc comparisons indicated that the greater AUC in the SUM than in the multisensory condition was significant both in the dyslexic ($M_{SUM} = 0.79$, $SD_{SUM} = 0.36$, $M_{multisensory} = 0.74$, $SD_{multisensory} = 0.36$, $p_{\text{corrrected}} = .011$) and the control group ($M_{SUM} = 0.87$, $SD_{SUM} = 0.32$, $M_{multisensory} = 0.74$, $SD_{multisensory} = 0.24$, $p_{\text{corrrected}} < .001$). The difference between groups was not significant either in the multisensory ($p_{\text{corrrected}} = .941$) or SUM conditions ($p_{\text{corrrected}} = .286$).

The analysis for the difference wave (multisensory – SUM) of the AUC has also replicated the effect of group ($F(1,76) = 4.47$, $p = .038$, $\eta^2_p = .056$) indicating that the difference in AUC between multisensory and SUM conditions was greater in the control (M = 0.21, SD = 0.12) than in the dyslexic group (M = 0.16, SD = 0.08). Moreover, in contrast to the results from the entire sample, an interaction between hemisphere, group, and sex (F(1,76) = 4.68, p = .034, η^2_p = .058) was found here. Post-hoc comparisons indicated that in the left hemisphere, males from the control group (M = 0.21, SD = 0.15) had a greater difference in AUC than males from the dyslexic group (M = 0.13, SD = 0.08, $p_{\text{corrrected}}$ = .028; see Figure 9), while this difference did not reach significance in the right hemisphere (M_{CON} = 0.20, SD_{CON} = 0.12, M_{DYS} = 0.13, SD_{DYS} = 0.09, $p_{\text{corrrected}}$ = .052). Differences between females from the control and the dyslexic group were not significant either in the left (M_{CON} = 0.19, SD_{CON} = 0.13, M_{DYS} = 0.19, SD_{DYS} = 0.10, $p_{\text{corrrected}}$ = .874) or the right hemisphere (M_{CON} = 0.22, SD_{CON} = 0.12, M_{DYS} = 0.18, SD_{DYS} = 0.07, $p_{\text{corrrected}}$ = .151). Furthermore, only females from the control group had a greater difference in AUC in the right compared to the left hemisphere ($p_{\text{corrrected}}$ = .034). No other effects or interactions were significant.

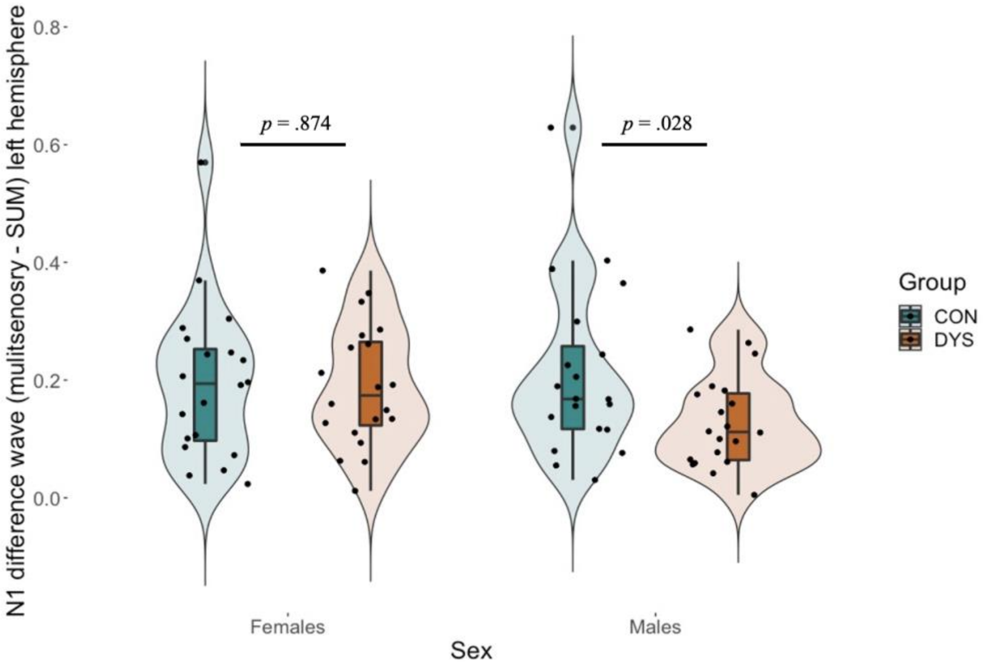

Figure 9. *Violin plots illustrating difference between conditions in the N1 component (left hemisphere) separately for females and males from the control (CON) and dyslexic (DYS) groups (n = 80).*

For the 50% fractional area latency, all results were replicated. There was a significant effect of condition (F(1,76) = 6.66, p = .012, η^2_p = .081) with the N1 component occurring later in the multisensory (M = 147.05, SD = 9.32) compared to the

SUM condition (*M* = 145.43, *SD* = 8.71) and the effect of sex (*F*(1,76) = 8.49, *p* = .005, η^2_p = .100) with the N1 component occurring later in males (*M* = 148.93, *SD* = 9.16) than in females (*M* = 143.55, *SD* = 7.11). No other effects or interactions were significant.

196-384 ms (N2 Component)

Results from the entire sample were replicated. For the AUC, there was a significant effect of condition (*F*(1,76) = 16.77, *p* < .001, η^2_p = .181) indicating that the AUC was greater in the SUM (*M* = 1.21, *SD* = 0.97) than in the multisensory condition (*M* = 1.06, *SD* = 0.91), the effect of hemisphere (*F*(1,76) = 32.16, *p* < .001, η^2_p = .297) indicating that the AUC was greater in the left (*M* = 1.23, *SD* = 1.03) compared to the right hemisphere (*M* = 1.04, *SD* = 0.84) and interactions between hemisphere and condition (*F*(1,76) = 6.14, *p* = .015, η^2_p = .075) as well as and between group and condition (*F*(1,76) = 5.64, *p* = .020, η^2_p = .069). For the hemisphere*condition interaction, post-hoc comparisons indicated that the AUC was greater in the SUM than in the multisensory condition both in the left (M_{SUM} = 1.30, SD_{SUM} = 1.06, $M_{multisensory}$ = 1.16, $SD_{multisensory}$ = 1.02, $p_{\text{corrrected}}$ < .001) and the right hemisphere (M_{SUM} = 1.13, SD_{SUM} = 0.90, $M_{multisensory}$ = 0.96, $SD_{multisensory}$ = 0.81, $p_{\text{corrrected}}$ < .001). Also, there was a greater AUC in the left than in the right hemisphere for both SUM and multisensory conditions ($p_{\text{corrrected}}$ < .001). For the group*condition interaction, post-hoc comparisons indicated that the AUC was greater in the SUM (*M* = 1.26, *SD* = 1.00) than in the multisensory condition (*M* = 1.02, *SD* = 0.92, $p_{\text{corrrected}}$ < .001) in the control group, while not in the dyslexic group (M_{SUM} = 1.16, SD_{SUM} = 0.95, $M_{multisensory}$ = 1.10, $SD_{multisensory}$ = 0.91, $p_{\text{corrrected}}$ = .228). The difference between groups was not significant either in the multisensory ($p_{\text{corrrected}}$ = .728) or SUM ($p_{\text{corrrected}}$ = .640) conditions.

The analysis for the difference wave (multisensory – SUM) of the AUC has replicated the results from the entire sample. There was a significant effect of hemisphere (*F*(1,76) = 5.46, *p* = .022, η^2_p = .067) indicating that there was a greater difference in AUC in the right (*M* = 0.37, *SD* = 0.27) compared to the left hemisphere (*M* = 0.34, *SD* = 0.24) and the effect of group (*F*(1,76) = 4.53, *p* = .037, η^2_p = .056) indicating that there was a greater difference in AUC in the control (*M* = 0.41, *SD* = 0.28) than in the dyslexic group (*M* = 0.29, *SD* = 0.20). No other effects or interactions were significant.

The analysis for the 50% fractional area latency, has also replicated the effect of group (*F*(1,76) = 5.18, *p* = .026, η^2_p = .064) with the N2 component occurring later in the dyslexic (*M* = 293.12, *SD* = 21.92) than in the control group (*M* = 282.82, *SD* = 18.29) and an interaction between condition, hemisphere, and sex ($F(1,76) = 4.80$, $p = .032$, $\eta^2_p = .059$). Again, post-hoc comparisons did not reveal any significant differences. No other effects or interactions were significant.

4.4.4. Relationships between reading and multisensory integration

In the group including both females and males, a positive correlation between pseudoword reading speed and the magnitude of multisensory integration (r(78) = .23, *p* = .044), as well as a negative correlation between pseudoword reading speed and the latency of the N2 component in the multisensory condition (r(78) = -.29, *p* = .009) were replicated (see Table 7). However, contrary to the results obtained from the entire sample of 88 participants, the latter correlation did not retain significance upon Bonferroni correction for 9 planned correlations at $p < .0056$. Moreover, unlike the results obtained in the whole sample, the correlation between latency in the N1 component in the multisensory condition and the magnitude of multisensory integration was not significant here (r(78) = -.19, *p* = .085).

In females only, a negative correlation between pseudoword reading speed and the latency of the N2 component in the multisensory condition (r(38) = -.39, *p* = .006) was replicated (see Table 8). However, this relationship did not withstand Bonferroni correction. Moreover, unlike the results obtained in the whole sample, a correlation between the magnitude of multisensory integration and the AUC of the difference wave in the N2 component was not significant here (r(38) = -.26, *p* = .052).

In males only, all results were replicated (Table 8). The magnitude of multisensory integration was positively correlated to pseudowords reading speed (r(38) = .31, *p* = .028) and negatively with the latency of the N2 component in the multisensory condition (r(38) = -.28, *p* = .038). Additionally, the AUC of the difference wave in the N1 component was positively correlated to pseudoword reading speed (r(38) = .39, *p* = .006). Alike the results from the entire sample, none of these correlations retained significance after Bonferroni correction.

Table 7. *Spearman's correlations between reading speed and behavioral and neural indices of multisensory integration in the whole subsample (n = 80).*

Variable	1.	2.	3.	4.	5.	6.
1. pseudowords/min	–					
2. magnitude of multisensory integration	.23*	–				
3. N1 AUC difference wave	.21	.17	–			
4. N1 50% FAL multisensory	-.09	-.19	-.12	–		
5. N2 AUC difference wave	.11	-.06	.21	.09	–	
6. N2 50% FAL multisensory	-.29**	-.19	-.30**	-.01	-.26*	–

Note. AUC – area-under-the-curve; 50% FAL – 50% fractional area latency.
***p* < .01 (two-tailed uncorrected); **p* < .05 (two-tailed uncorrected)

Table 8. *Spearman's correlations between reading speed and behavioral and neural indices of multisensory integration separately for females and males (n = 80).*

	Females (n = 40)						**Males (n = 40)**					
Variable	1.	2.	3.	4.	5.	6.	1.	2.	3.	4.	5.	6.
1. pseudowords/min	–						–					
2. magnitude of multisensory integration	.08	–					.31*	–				
3. N1 AUC difference wave	.04	.21	–				.39**	.12	–			
4. N1 50% FAL multisensory	-.00	-.21	-.12	–			-.07	-.09	-.01	–		
5. N2 AUC difference wave	.20	-.26	.08	.03	–		.10	.10	.35*	.16	–	
6. N2 50% FAL multisensory	-.39**	-.12	.33*	.01	-.24	–	-.18	-.28*	-.33*	.03	-.27*	–

Note. AUC – area-under-the-curve; 50% FAL – 50% fractional area latency.
***p* < .01 (one-tailed uncorrected); **p* < .05 (one-tailed uncorrected)

5. MULTISENSORY INTEGRATION – DISCUSSION

The results reported in this section addressed the first aim of the thesis, regarding the assessment of potential sex-specific effects in multisensory integration in dyslexia. This was based on a meta-analysis of multisensory and unisensory temporal skills in dyslexia, which indicated that studies that did not match participants by sex reported larger effect sizes than sex-matched studies (Meilleur et al., 2020). Furthermore, since dyslexia is more frequently diagnosed in males (Di Folco et al., 2022; Quinn & Wagner, 2015; Yang et al., 2022), and some studies have reported sex differences in the neural correlates of dyslexia (Altarelli et al., 2014, 2013; Evans et al., 2014; Müller-Axt et al., 2025), the cognitive basis of dyslexia may also vary between females and males (Chan et al., 2007; Jiménez et al., 2011). Specifically, based on previous study on the multisensory speech processing task in individuals with ASD, which reported worse performance in boys with ASD (Ross et al., 2015), I expected to find a similar pattern in dyslexia, with males exhibiting greater impairments than females.

At the behavioral level, participants' RTs in the multisensory condition were faster than in the unisensory conditions – a typical effect observed in numerous studies using the RTE task (e.g., Harrar et al., 2014; Mahoney et al., 2011; Molholm et al., 2004). However, in contrast to the previous RTE study on dyslexia, which found generally slower RTs in dyslexic than in control participants across all conditions (Harrar et al., 2014), the current study did not identify any significant group or sex differences in median RTs. Nevertheless, a comparison of RT gains in multisensory versus unisensory conditions based on the RMI (Miller, 1982) indicated that the dyslexic group benefited less from multisensory input than the control group. Consistent with predictions, there was also a significant interaction between group and sex, revealing that the main effect of group was driven solely by males with dyslexia. A similar finding of reduced RT facilitation in the multisensory condition for the dyslexic group was previously reported by Harrar and colleagues (2014), although their method of analyzing the RMI differed from the one applied here. Instead of calculating the AUC for a range of violated RTs in the entire sample, as recommended by Mahoney & Verghese (2019), they examined the number of violated percentile bins across the entire RT distribution (Harrar et al., 2014). Additionally, they did not analyze the interaction between group and sex, likely due to their smaller sample size (9 females and 8 males in the dyslexic group; 10 females and 9 males in the control group), which may have lacked the statistical power to detect a two-way interaction. Interestingly, the reduction in multisensory integration observed in males with dyslexia in the current study cannot be attributed to a general pattern of slower reaction times, as no differences in median RTs were found. However, independence between these two measures has been previously observed as older adults exhibit slower reaction times than younger adults but, at the same time, gain greater benefits from multisensory inputs, than their younger counterparts (Laurienti et al., 2006; Mahoney et al., 2011).

Although the current study is the first to report sex differences in multisensory integration among individuals with dyslexia, this finding may partly explain the discrepancies in effect sizes observed in studies of unisensory and multisensory temporal processing in dyslexia, depending on whether participants were matched by sex (Meilleur et al., 2020). The results obtained here also highlight the need for further research on sex differences in multisensory integration in dyslexia across different age groups, stimuli, and task conditions to better understand the scope of these deficits. Replication in other age groups is especially important, as a positive relationship between age and the magnitude of multisensory integration has been found. This aligns with previous studies reporting a greater magnitude of multisensory integration during childhood with increasing age (Brandwein et al., 2011), in young adults compared to adolescents (Ostrolenk et al., 2019), and in older adults compared to younger ones (Laurienti et al., 2006; Mahoney et al., 2011), indicating a consistent pattern of increased benefit from multisensory input with age. Therefore, it would be worthwhile to investigate whether the sex differences identified here are already present in younger children or whether females with dyslexia gradually "catch up" to control females as they grow older.

Interestingly, at the behavioral level, the only significant interaction between group and sex was observed in the multisensory integration task, while no such interaction was detected in any other reading or reading-related tasks. This suggests that the deficit in multisensory integration observed in males with dyslexia is not linked to differences in other reading-related cognitive abilities; but rather is an additional risk factor of dyslexia in males. Notably, participants with dyslexia in this study did not report any comorbid neuropsychiatric conditions, such as ADHD, making it unlikely that the results were influenced by co-occurring diagnoses. Regarding the overall differences between females and males, independent of dyslexia status, a main effect of sex was observed solely in the orthographic awareness task, where females outperformed males. However, this difference was not statistically significant after adjusting for multiple comparisons.

Given the previous findings on general sex differences in various reading-related cognitive abilities across different languages (Arnett et al., 2017; Chan et al., 2007; Jiménez et al., 2011), these results should be replicated in a larger sample from the Polish general population.

Moreover, a main effect of group revealed that participants with dyslexia performed worse in most reading-related tasks, including phonological awareness, working memory, and RAN. This finding aligns with numerous studies reporting deficits in these skills among individuals with dyslexia (Araújo & Faísca, 2019; Carioti et al., 2021; Chen et al., 2021; Melby-Lervåg et al., 2012; Peng et al., 2017; Reis et al., 2020). The only exception was the visual attention task. While the dyslexic group scored lower on the perception speed measure, no significant differences were found in the number of errors or omissions. Previous research has similarly identified slow perceptual processing as a characteristic of dyslexia (McLean et al., 2011; Stenneken et al., 2011). Additionally, a review of studies on visual selective attention highlights poorer accuracy and slower RTs among children with dyslexia, though the findings are rather heterogeneous (Hokken et al., 2023). Furthermore, the authors suggest that differences in tasks involving stimuli that map onto phonological codes (e.g., letters and digits) may reflect phonological rather than attentional deficits in dyslexia (Hokken et al., 2023). Supporting this, one study found that children with dyslexia performed worse on a rapid processing task with letter and digit stimuli but not with symbol stimuli (Ziegler, Pech-Georgel et al., 2010). Given that the current study utilized task with digit stimuli, the observed differences in perception speed measure may stem from underlying phonological deficits rather than attentional ones.

At the neural level, systematic differences between the multisensory and the sum of unisensory conditions were observed across all analyzed time windows. Specifically, a sub-additivity effect was identified, where the neural response to the SUM condition was greater than that to the multisensory condition. This type of effect has been previously reported in ERP studies on multisensory integration (e.g., Klucharev et al., 2003; Kronschnabel et al., 2014), although a reversed super-additivity effect has also been observed (e.g., Molholm et al., 2020; Santangelo et al., 2008). Additionally, in the P1 component, the SUM condition was associated with delayed latency compared to the multisensory condition, whereas the opposite pattern was found in the N1 component. In the N1 component, a greater neural response in the SUM than in the multisensory condition was observed in both the dyslexic and control groups, suggesting that in both groups stimuli were processed differently depending on whether they were presented simultaneously or individually. However, when evaluating the difference wave between the SUM and multisensory conditions, a greater difference was observed in the control than in the dyslexic group. Moreover, in the N2 component, a significant difference between conditions was present only in the control group, while the dyslexic group exhibited delayed component latency. Yet, the findings regarding the N2 component should be interpreted with caution, as differences occurring after 200 ms post-stimulus may be linked to motor responses, which are represented twice in the SUM condition (Giard & Besle, 2010). Nevertheless, differences between groups were also found in the N1 component, which are less likely to be influenced by motor responses, indicating atypical multisensory processing in dyslexia.

These results diverge from previous ERP studies on multisensory integration in dyslexia, which either found no significant group differences (Francisco, 2017) or reported differences in the P1 component that were attributed to delayed neural responses to unisensory stimuli in the dyslexic group (Kronschnabel et al., 2014). In the current study, the only significant difference between groups in the unisensory conditions was found in the visual-alone condition, with delayed latency of the N2 component in the dyslexic group. Therefore, it is unlikely that all group differences between the multisensory and SUM conditions identified here are due to atypical responses to unisensory stimuli in the dyslexic group, as suggested by Kronschnabel and colleagues (2014). Nevertheless, those studies employed linguistic stimuli, which limits direct comparison with the current findings. One previous study also reported delayed latency in the P2 and P3 components for visual and multisensory conditions among dyslexic males in response to non-linguistic stimuli in a choice-reaction task (Breznitz & Meyler, 2003). However, this delay was also linked to slower RTs in the multisensory condition in dyslexia. In contrast, no effects of sex or dyslexia status on median RTs were observed in the current study, which does not support the notion of generally slower processing speed for low-level stimuli in the dyslexic group. Again, comparisons between studies are limited due to differences in task requirements and the components that were analyzed. Interestingly, while no group differences were observed here in median RTs during the RTE task, the dyslexic group scored lower than the control group on the perception speed score in the visual attention task with digit stimuli. This further supports the notion that processing speed in dyslexia may vary depending on the specific tasks and stimuli used.

In contrast to the behavioral results, no interaction between group and sex was detected in any ERP component in the entire sample of 88 participants. This may indicate that both females and males with dyslexia exhibit atypical neural processing of multisensory information. Alternatively, although the current sample size was relatively large for an ERP study (compared to 13 participants with dyslexia and 22 controls in Kronschnabel et al., 2014, and 20 dyslexic participants and 17 controls in Francisco, 2017), it might still have been too small to detect an interaction between group and sex. However, in a subsample of 80 participants matched for nonverbal IQ, a significant interaction between hemisphere, group, and sex in the N1 component was found. Specifically, in the left hemisphere, the sub-additivity effect was smaller in males with dyslexia compared to control males, whereas no such differences were observed in females. This finding aligns with the behavioral results, suggesting more pronounced deficits in multisensory integration in males than in females with dyslexia. Future replication studies of this result with dyslexic and control groups better matched for nonverbal IQ are necessary, as previous research has indicated that multisensory gains in simple detection tasks can predict nonverbal IQ in children (Denervaud et al., 2020). Regardless of dyslexia status, general sex differences in the N1 component were also observed, with females exhibiting greater responses and shorter latencies in both multisensory and SUM conditions than males. Similar patterns of stronger and faster N1 responses in females have been reported in previous ERP studies using linguistic stimuli (Sato, 2020), indicating broader sex differences in the N1 component.

Furthermore, the magnitude of multisensory integration positively correlated with pseudoword reading speed, supporting the idea that a deficit in low-level multisensory processing contributes to reading difficulties in dyslexia. This also aligns with findings by Harrar et al. (2014), who reported a similar correlation between multisensory integration and the discrepancy scores between literacy and non-verbal abilities. However, when correlations were analyzed separately for females and males, this relationship was significant only for male participants. Across the entire sample, the magnitude of multisensory integration was also linked to earlier N1 component latency in the multisensory condition. Relationships between behavioral and neurophysiological measures of multisensory integration have been previously observed for the amplitude of the difference wave in the N1 component (Brandwein et al., 2011), while the latency was not analyzed. Furthermore, earlier N2 component latency in the multisensory condition was linked to better pseudoword reading speed, which was further confirmed in females.

This suggests potential sex differences in the relationship between neural indices of multisensory integration and reading skills. However, after correcting for multiple comparisons, the only significant relationship was the negative correlation between reading speed and N2 component latency in the multisensory condition, observed both in the entire sample and specifically among females. Therefore, the other correlations should be interpreted cautiously and further replicated with larger samples. Moreover, in a subsample of 80 participants matched for nonverbal IQ, none of these correlations remained significant after Bonferroni correction, suggesting weak associations between these variables.

In conclusion, the current results point to sex differences in multisensory integration of simple non-linguistic stimuli in dyslexia, as only males showed reduced RT facilitation to multisensory stimuli at the behavioral level. At the neural level, both females and males with dyslexia exhibited differences in processing multisensory stimuli in the N1 and N2 components compared to the control group. However, within a subsample matched for nonverbal IQ, evidence for atypical multisensory processing in the N1 component was identified specifically in males with dyslexia. These findings indicate that sex plays an important role in cognitive skills related to reading and highlight the necessity for further research to explore the role of sex differences in the etiology of neurodevelopmental disorders.

6. NEURAL NOISE – MATERIALS & METHODS

6.1. Participants

The total sample consisted of 120 participants aged between 15.09 and 24.95 years (*M* = 19.47, *SD* = 3.06), including 60 individuals diagnosed with dyslexia and 60 typical readers matched for sex, age, and family socio-economic status, based on the mother's and father's years of education (see Table 9).

A significant between-group difference (*t*(-16.04) = 113.87, *p* < .001, *d* = -2.93, BF_{10} > 10000) was found in the ARHQ-PL questionnaire (Bogdanowicz et al., 2015) where a higher score indicates a greater risk of dyslexia, with the dyslexic group scoring higher (*M* = 51.50, *SD* = 9.70) than the control group (*M* = 25.47, *SD* = 8.00). Although all participants had typical IQ, a significant between-group difference was observed on the IQ scale (*t*(117) = 3.70, *p* < .001, *d* = 0.68, BF_{10} = 75.31), with the control group (*M* = 111.12, *SD* = 10.43) scoring higher than the dyslexic group (*M* = 103.56, *SD* = 11.83). A significant between-group difference was also found on the nonverbal IQ subscale (*t*(118) = 2.42, *p* = .017, *d* = 0.44, BF_{10} = 2.63), with the control group (*M* = 11.62, *SD* = 2.57) scoring higher than the dyslexic group (*M* = 10.40, *SD* = 2.94), although the Bayes Factor did not provide conclusive evidence for either the alternative or null hypothesis.

Since most of the results reported in this section are non-significant, Bayesian statistics were calculated alongside frequentist statistics to compare the strength of evidence for the null and alternative hypotheses.

The neural noise hypothesis of dyslexia (Hancock et al., 2017) does not predict any differences between females and males at either the cognitive or neural level. However, given identified sex differences in multisensory integration, the results reported here were also reanalyzed to account for the effect of sex. As these models likewise yielded non-significant results, only models assessing the effect of group are presented.

Table 9. *Descriptive statistics for demographic characteristics for the entire sample (n = 120). For all comparisons, t statistics, degrees of freedom (in brackets), p-values, Cohen's d and Bayes Factor indicating ratio of the likelihood of an alternative hypothesis to a null hypothesis (BF_{10}) are provided.*

	DYS (28 F, 32 M)		CON (28 F, 32 M)		*t* (df)	*p*	Cohen's *d*	BF_{10}
	M	*SD*	*M*	*SD*				
Age	19.41	3.18	19.54	2.96	0.25 (118)	.806	0.05	0.20
Mother's education (years)	17.20	3.36	16.58	2.28	-1.19 (103.89)	.235	-0.22	0.37
Father's education (years)	16.12[a]	3.10[a]	17.13[a]	3.27[a]	1.71 (114)	.091	0.32	0.73
IQ	103.56[b]	11.83[b]	111.12	10.43	3.70 (117)	**< .001**	0.68	75.31
Nonverbal IQ (scaled score)	10.40	2.94	11.62	2.57	2.42 (118)	**.017**	0.44	2.63
ARHQ-PL	51.50	9.70	25.47	8.00	-16.04 (113.87)	**< .001**	-2.93	>10000

Note. DYS – dyslexic group; CON – control group; F – females, M – males. ARHQ-PL – Polish version of the Adult Reading History Questionnaire. Boldface indicates statistical significance at $p < .05$ level (uncorrected).
[a] $n = 58$ (two participants did not provide information about the father's education);
[b] $n = 59$ (one participant did not attempt a verbal subtest of the scale, thus his overall IQ could not be calculated)

6.2. EEG procedure

EEG data for the E/I balance assessment were recorded during two conditions: a 5-minute eyes-open resting state and a spoken language comprehension task. The paradigm was created using Presentation software (Version 20.1, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com).

During the resting state, participants were instructed to relax and keep their gaze fixed on a centrally displayed white cross on a black background. After 5 minutes, the spoken language comprehension task began automatically (see Figure 10). The task involved listening to 3- to 5-word sentences generated using a speech synthesizer, delivered binaurally through sound-isolating earphones. After hearing each sentence, participants indicated whether the statement was true or false by pressing a corresponding button. The task included a total of 256 sentences, evenly split into 128 true statements (e.g., "Plants need water", "Actors play in movies", "Summer is warmer than winter") and 128 false statements (e.g., "Dogs can fly", Bikes have seven wheels", "Egg is a leaf vegetable").

The sentences were presented in random order across two blocks of 128 trials. Each trial began with a white fixation cross displayed on a black background for 500 ms, followed by a blank screen lasting 500, 600, 700, or 800 ms (durations set randomly and equiprobably). Next, the auditory sentence was presented. Durations of sentences ranged between 1.17 and 2.78 second and did not differ between true (*M* = 1.82 seconds, *SD* = 0.29) and false sentences (*M* = 1.82 seconds, *SD* = 0.32; *t*(254) = -0.21, *p* = .835, BF_{10} = 0.14). After each sentence, a blank screen was displayed for 1000 ms to allow a behavioral response before the next trial began.

To minimize fatigue, participants were given a 1-minute break between the two blocks of trials and it took approximately 15 minutes to complete the task.

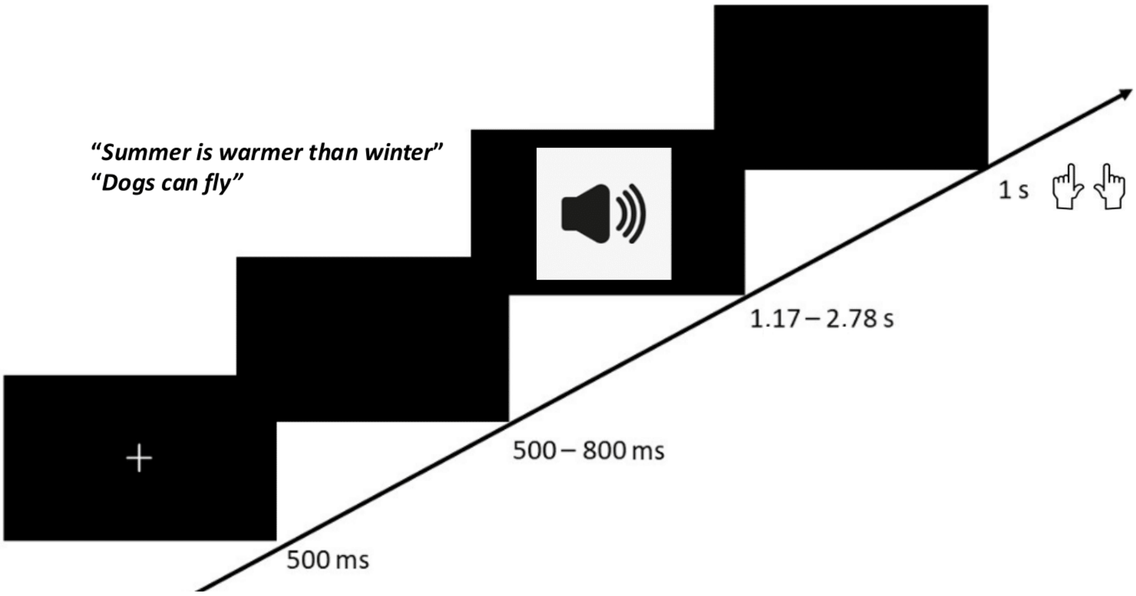

Figure 10. *Schematic illustration of the spoken language task. A total of 128 true (e.g., "Summer is warmer than winter) and 128 false sentences (e.g., "Dogs can fly") were presented across 2 blocks of trials. Sentences were presented in a random order.*

6.3. Statistical analyses

All frequentist statistics were performed on IBM SPSS Statistics v.29 and post-hoc pairwise comparisons were reported with Bonferroni-corrected *p*-values. In turn, Bayesian statistics were conducted using JASP (JASP Team, 2023). For Bayesian *t*-tests and correlations, the BF_{10} value was reported, representing the ratio of the likelihood of the alternative hypothesis to the null hypothesis. For Bayesian ANOVA, Bayes Factors for the inclusion of specific effects (BF_{incl}) were reported using the 'across matched model' option, as recommended by Keysers et al. (2020). These were calculated as the likelihood ratio of models including a specific factor compared to equivalent models excluding that factor. BF_{10} or BF_{incl} values > 3 and $< \frac{1}{3}$ were interpreted as evidence supporting the alternative and null hypotheses, respectively, while values between $\frac{1}{3}$ and 3 were considered indicative of insufficient evidence to support either hypothesis (Keysers et al., 2020).

6.3.1. Reading and reading-related tasks

For every reading and reading-related task, a separate *t*-test was conducted to analyze differences between dyslexic and control groups. Cohen's *d* was reported as the effect size measure. Effect sizes were interpreted as small ($d = 0.2$), medium ($d = 0.5$) or large ($d = 0.8$). Apart from reporting the uncorrected *p*-values, the Bonferroni corrected *p*-values for multiple tests (16 measures from all reading-related tasks) at $p < .0031$ were also reported.

6.3.2. EEG data

First, the continuous EEG signal was preprocessed using EEGLAB (Delorme & Makeig, 2004). Data were filtered between 0.5 and 45 Hz using a 4th-order Butterworth filter and re-referenced to the average of both ear electrodes. Segments recorded during breaks between blocks of trials and bad channels were manually removed. The number of removed channels ranged from 0 to 4 channels per participant ($M = 0.19$, $SD = 0.63$). Then, ICA was performed, and components were automatically labeled by ICLabel (Pion-Tonachini et al., 2019). Components labeled with 50-100% probability as eye blinks, muscle activity, heart activity, channel noise, line noise, as well as components labeled with 0-50% probability as brain activity were excluded. Components labeled as "other" were visually inspected, and those recognized as eye blinks or muscle activity were also removed. The number of rejected components ranged from 11 to 46 per participant ($M = 28.43$, $SD = 7.26$). Previously removed channels were interpolated using nearest neighbor spline method (Perrin et al., 1987, 1989).

The preprocessed data were then split into signals from the 5-minute resting-state condition and the spoken language comprehension task using MNE (Gramfort et al., 2013) and custom Python scripts. Signal from the spoken language task was segmented based on markers indicating sentence boundaries. Only trials in which participants have given correct responses within 0-1000 ms after the sentence were included. Signal from each trial was then multiplied by a Tukey window ($\alpha = 0.01$) to normalize signal amplitudes at the start and end of trials, allowing smooth concatenation of task-related signals into a continuous dataset reflecting only periods of sentence presentations.

Both the resting-state and task-related signals were divided into 2-second segments. An automatic rejection threshold of ±200 μV was applied to exclude segments with excessive amplitudes. The final number of epochs retained in the analysis ranged between 140 and 150 ($M = 149.66$, $SD = 1.20$) for the resting-state data and between 102 and 226 ($M = 178.24$, $SD = 28.94$) for the task-related data. A 2x2 (group, condition) repeated measures ANOVA revealed a significant effect of condition ($F(1,117) = 116.30$, $p < .001$, $\eta^2_p = .498$, $BF_{incl} > 10000$) with a higher number of epochs retained in the analysis for the task-related data compared to the resting state data. The effect of group and the interaction between group and condition were not significant.

Next, power spectral density (PSD) for the 0.5-45 Hz range was computed for every artifact-free epoch using Welch's method on 2-second segments windowed with a Hamming window with no overlap. PSD values were averaged for each participant and channel separately for the resting-state and task conditions. Aperiodic and periodic (oscillatory) components of the PSD were then parameterized using the FOOOF method (Donoghue et al., 2020), for the 1-43 Hz range. Two broadband parameters were extracted: exponent (indicating steepness of the power spectrum) and offset (indicating uniform shift in power across the entire power spectrum). Aperiodic-adjusted oscillatory power, bandwidth, and center frequency for the theta (4-7 Hz), alpha (7-14 Hz), beta (14-30 Hz), and gamma (30-43 Hz) bands were also extracted. Nevertheless, as peaks above the aperiodic component were not consistently detected in theta and gamma bands in the majority of participants, analyses were performed only for the alpha and beta bands. Results for periodic parameters other than beta power were exploratory, as they were not directly identified as E/I balance biomarkers; therefore, they are reported in the Supplementary Material.

First, following previous studies which analyzed aperiodic components of the EEG signal (e.g., Manyukhina et al., 2022; McSweeney et al., 2021; Pei et al., 2023), aperiodic measures (exponent and offset) were averaged across all electrodes and analyzed using a 2x2 (group, condition) repeated measures ANOVA. Since age was correlated with both the exponent and offset, it was included as a covariate in the models.

Next, exponent and offset values were averaged across electrodes over the left (F7, FT7, FC5) and right IFG (F8, FT8, FC6) as well as over the left (T7, TP7, TP9) and right STS (T8, TP8, TP10), to explore potential regional differences restricted to the brain language network. These electrodes were selected based on previous works analyzing correspondence between electrodes and underlying brain regions (Giacometti et al., 2014; Scrivener & Reader, 2022). For these analyses, a 2x2x2x2 (group, condition, hemisphere, region) repeated measures ANOVA with age as a covariate was conducted.

For periodic activity (alpha and beta oscillations), analyses were performed using a similar 2x2x2x2 ANOVA model for the same clusters of frontal and temporal electrodes. However, in these analyses, age was not included as a covariate due to non-significant correlations between variables.

Furthermore, following the previous work which demonstrated differences in aperiodic and periodic components in dyslexia (Turri et al., 2023), analyses were performed for the same cluster of parieto-occipital electrodes from the left (PO7, PO3, O1) and the right hemisphere (PO8, PO4, O2). For the exponent and offset, a 2x2x2 (group, condition, hemisphere) repeated measures ANOVA with age included as a covariate was employed. For alpha and beta results, analyses were performed with a similar model but without the effect of age included as a covariate due to non-significant correlations between variables.

7. NEURAL NOISE – RESULTS

7.1. Reading and reading-related tasks

In most reading and reading-related tasks, a significant between-group difference was found with the dyslexic group performing worse than the control group (see Table 10). The only exception was the visual attention test. In this task, participants with dyslexia scored lower than the controls only in the perception speed score, while no significant differences were observed in the number of errors (perceptual discrimination score) or the number of omissions (selective attention score). The effect sizes were large ($d \geq 0.8$) for reading tasks (words and pseudowords read per minute and text reading time in the reading comprehension task), phonological tasks (phoneme deletion and spoonerism tasks), short-term and working memory tasks (digits forward and backward), and the orthographic awareness task. In turn, the effect sizes were medium ($d \geq 0.5$) for all RAN subsets, as well as for the perception speed score.

Table 10. *Behavioral results from reading and reading-related tasks for the entire sample (n = 120). For all comparisons, t statistics, degrees of freedom (in brackets), p-values, Cohen's d and Bayes Factor indicating ratio of the likelihood of an alternative hypothesis to a null hypothesis (BF_{10}) are provided.*

	DYS (28 F, 32 M)		CON (28 F, 32 M)		*t* (df)	*p*	Cohen's *d*	BF$_{10}$
	M	*SD*	*M*	*SD*				
words/min	108.38	20.93	134.57	13.29	8.18 (99.90)	< **.001***	1.49	>10000
pseudowords/min	56.75	14.16	83.43	17.04	9.33 (118)	< **.001***	1.70	>10000
RAN objects (s)	32.12	5.11	28.70	4.43	-3.92 (118)	< **.001***	-0.72	149.93
RAN colors (s)	35.83	6.82	31.18	5.73	-4.04 (118)	< **.001***	-0.74	229.96
RAN digits (s)	19.32	4.61	16.25	2.94	-4.34 (100.28)	< **.001***	-0.79	642.86
RAN letters (s)	22.70	4.53	19.68	3.16	-4.23 (105.42)	< **.001***	-0.77	433.23
reading comprehension (s)	64.47	20.13	43.72	9.63	-7.20 (84.66)	< **.001***	-1.32	>10000
phoneme deletion (% correct)	76.41	24.68	91.47	9.07	4.44 (74.66)	< **.001***	0.81	898.25
spoonerisms phonemes (% correct)	54.29	35.42	82.74	22.06	5.28 (98.78)	< **.001***	0.96	>10000
spoonerisms syllables (% correct)	46.94	30.61	73.06	23.98	5.20 (111.62)	< **.001***	0.95	>10000
orthographic awareness (accuracy/time)	0.33	0.13	0.53	0.14	8.12 (118)	< **.001***	1.48	>10000
perception speed (sten score)	3.32	2.04	4.50	1.67	3.48 (118)	< **.001***	0.64	38.71
perceptual discrimination (percentile score)	92.03	16.49	95.03	0.18	1.41 (59.01)	.164	0.26	0.48
selective attention (quartile score)	2.08	1.03	2.10	1.00	0.09 (118)	.929	0.02	0.20
digits forward	5.53	1.64	6.98	1.95	4.40 (118)	< **.001***	0.80	792.55
digits backward	5.25	1.49	7.33	2.25	5.99 (102.59)	< **.001***	1.09	>10000

Note. DYS – dyslexic group; CON – control group; F – females, M – males. RAN – rapid automatized naming. Boldface indicates statistical significance at $p < .05$ level (uncorrected).
*Significance after Bonferroni correction at $p < .0031$

7.2. EEG results

The results are provided for 119 participants – 59 in the dyslexic and 60 in the control group, since due to a technical error the signal from one person (a female from the dyslexic group) was not recorded during most of the language task.

In line with previous studies (Cellier et al., 2021; McSweeney et al., 2021; Schaworonkow & Voytek, 2021; Voytek et al., 2015) age was negatively correlated with both the exponent (r = -.27, p = .003, BF_{10} = 7.96) and offset (r = -.40, p < .001, BF_{10} = 3174.29), therefore age was included as a covariate in these models.

Plots showing power spectra from the left STS and the results for the exponent, offset, and beta power are presented in Figure 11, while descriptive statistics for all EEG results separately for dyslexic and control groups are provided in Table 11.

7.2.1. Exponent

Values averaged across all electrodes

For the exponent averaged across all electrodes, there was a significant effect of age (F(1,116) = 8.90, p = .003, η^2_p = .071, BF_{incl} = 10.47), while the effects of condition (F(1,116) = 2.32, p = .131, η^2_p = .020, BF_{incl} = 0.39) and group (F(1,116) = 0.08, p = .779, η^2_p = .001, BF_{incl} = 0.40) were not significant and Bayes Factor did not provide conclusive evidence for either inclusion or exclusion. Interaction between group and condition was not significant and Bayes Factor indicated against including it in the model (F(1,116) = 0.16, p = .689, η^2_p = .001, BF_{incl} = 0.21).

Frontal and temporal electrodes

There were significant effects of age (F(1,116) = 14.00, p < .001, η^2_p = .108, BF_{incl} = 11.46) and condition (F(1,116) = 4.06, p = .046, η^2_p = .034, BF_{incl} = 1.88), however, Bayes Factor did not provide evidence for either including or excluding the condition factor. Moreover, post-hoc comparison did not reveal significant differences between the exponent at rest (M = 1.51, SD = 0.17) and during the language task (M = 1.51, SD = 0.18, $p_{corrected}$ = .546). There was also a significant interaction between region and group, although Bayes Factor indicated against including it in the model (F(1,116) = 4.44, p = .037, η^2_p = .037, BF_{incl} = 0.25). Post-hoc comparisons revealed that the exponent was higher in the frontal compared to the temporal region both in the dyslexic ($M_{frontal}$ = 1.54, $SD_{frontal}$ = 0.15, $M_{temporal}$ = 1.49, $SD_{temporal}$ = 0.18, $p_{corrected}$ < .001) and the control group ($M_{frontal}$ = 1.54, $SD_{frontal}$ = 0.17, $M_{temporal}$ = 1.46, $SD_{temporal}$ = 0.20,

$p_{\text{corrected}} < .001$). The difference between groups was not significant either in the frontal ($p_{\text{corrected}} = .858$) or temporal region ($p_{\text{corrected}} = .441$). The effects of region ($F(1,116) = 1.17$, $p = .282$, $\eta^2_p = .010$, $BF_{incl} > 10000$) and hemisphere ($F(1,116) = 1.17$, $p = .282$, $\eta^2_p = .010$, $BF_{incl} = 12.48$) were not significant, although Bayes Factor indicated in favor of including them in the model. Furthermore, the interactions between condition and group ($F(1,116) = 0.18$, $p = .673$, $\eta^2_p = .002$, $BF_{incl} = 3.70$), as well as between region, hemisphere, and condition ($F(1,116) = 0.11$, $p = .747$, $\eta^2_p = .001$, $BF_{incl} = 7.83$) were not significant, however Bayes Factor indicated in favor of including them in the model. The effect of group was not significant, while Bayes Factor did not provide conclusive evidence for either inclusion or exclusion ($F(1,116) = 0.12$, $p = .733$, $\eta^2_p = .001$, $BF_{incl} = 1.19$). Any other interactions were not significant and Bayes Factor indicated against including them in the model. Since Bayes Factor suggested the inclusion of the condition*group interaction in the model, follow-up Bayesian *t*-tests were conducted to verify whether this was driven by differences between control and dyslexic groups in either condition. The results, however, supported the null hypothesis in both the resting state condition ($M_{DYS} = 1.51$, $SD_{DYS} = 0.16$, $M_{CON} = 1.50$, $SD_{CON} = 0.19$, $BF_{10} = 0.22$) and during the language task ($M_{DYS} = 1.52$, $SD_{DYS} = 0.17$, $M_{CON} = 1.51$, $SD_{CON} = 0.19$, $BF_{10} = 0.20$).

Parieto-occipital electrodes

There were significant effects of age ($F(1,116) = 5.22$, $p = .024$, $\eta^2_p = .043$, $BF_{incl} = 2.07$) and hemisphere ($F(1,116) = 6.37$, $p = .013$, $\eta^2_p = .052$, $BF_{incl} > 10000$) and post-hoc comparison revealed that the exponent was lower in the left ($M = 1.46$, $SD = 0.21$) than in the right hemisphere ($M = 1.53$, $SD = 0.19$, $p_{\text{corrected}} < .001$). The effect of group was not significant; however, Bayes Factor did not provide conclusive evidence for either inclusion or exclusion ($F(1,116) = 0.07$, $p = .786$, $\eta^2_p = .001$, $BF_{incl} = 0.65$). Any other effects or interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

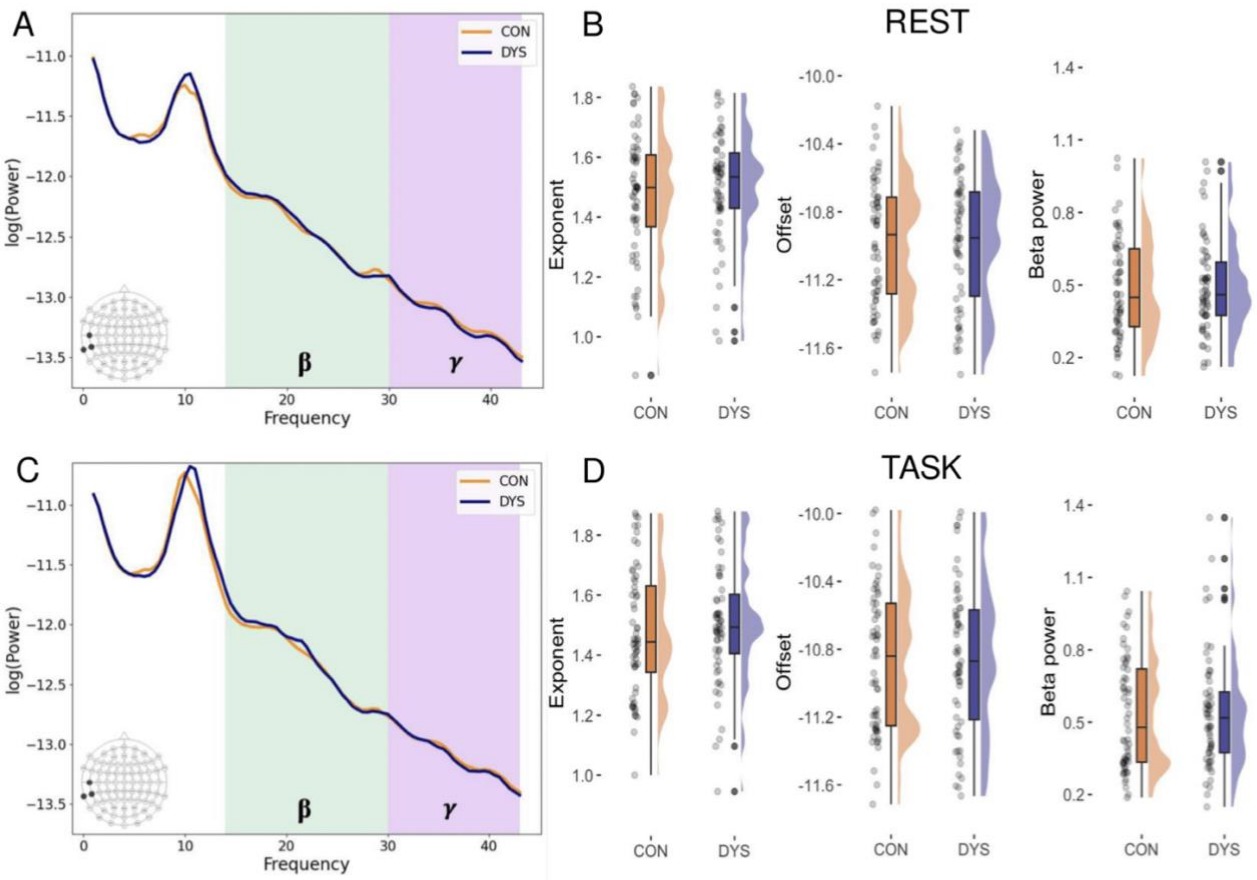

Figure 11. *(A) Power spectral densities averaged across 3 electrodes (T7, TP7, TP9) corresponding to the left superior temporal sulcus (STS) separately for control (CON) and dyslexic (DYS) groups at rest and **(C)** during the language task. **(B)** Plots illustrating results for the exponent, offset, and the beta power from the left STS electrodes at rest and **(D)** during the language task.*

7.2.2. Offset

Values averaged across all electrodes

For the offset averaged across all electrodes, there were significant effects of age ($F(1,116) = 22.57$, $p < .001$, $\eta^2_p = .163$, $BF_{incl} = 1762.19$) and condition ($F(1,116) = 23.04$, $p < .001$, $\eta^2_p = .166$, $BF_{incl} > 10000$) and post hoc comparison revealed that the offset was lower in the resting state ($M = -10.80$, $SD = 0.21$) compared to the language task ($M = -10.67$, $SD = 0.26$, $p_{corrected} < .001$). The effect of group was not significant while Bayes Factor did not provide conclusive evidence for either inclusion or exclusion ($F(1,116) = 0.00$, $p = .964$, $\eta^2_p = .000$, $BF_{incl} = 0.54$). Interaction between group and condition was not significant and Bayes Factor indicated against including it in the model ($F(1,116) = 0.07$, $p = .795$, $\eta^2_p = .001$, $BF_{incl} = 0.22$).

Frontal and temporal electrodes

There were significant effects of condition ($F(1,116) = 20.88$, $p < .001$, $\eta^2_p = .153$, $BF_{incl} > 10000$) and region ($F(1,116) = 6.18$, $p = .014$, $\eta^2_p = .051$, $BF_{incl} > 10000$). For the main effect of condition, post-hoc comparison revealed that the offset was lower in the resting state condition ($M = -10.88$, $SD = 0.33$) compared to the language task ($M = -10.76$, $SD = 0.38$, $p_{corrected} < .001$), while for the main effect of region, post-hoc comparison indicated that the offset was lower in the temporal ($M = -10.94$, $SD = 0.37$) than in the frontal region ($M = -10.69$, $SD = 0.34$, $p_{corrected} < .001$). There was also a significant effect of age ($F(1,116) = 20.84$, $p < .001$, $\eta^2_p = .152$, $BF_{incl} = 0.23$) as well as interaction between condition and hemisphere, ($F(1,116) = 4.35$, $p = .039$, $\eta^2_p = .036$, $BF_{incl} = 0.21$), although Bayes Factor indicated against including them in the model. Post-hoc comparisons for the condition*hemisphere interaction revealed that the offset was lower in the resting state condition compared to the language task both in the left ($M_{rest} = -10.85$, $SD_{rest} = 0.34$, $M_{task} = -10.73$, $SD_{task} = 0.40$, $p_{corrected} < .001$) and in the right hemisphere ($M_{rest} = -10.91$, $SD_{rest} = 0.31$, $M_{task} = -10.79$, $SD_{task} = 0.37$, $p_{corrected} < .001$) and that the offset was lower in the right compared to the left hemisphere both at rest ($p_{corrected} < .001$) and during the language task ($p_{corrected} < .001$). The interactions between region and condition ($F(1,116) = 1.76$, $p = .187$, $\eta^2_p = .015$, $BF_{incl} > 10000$), hemisphere and group ($F(1,116) = 1.58$, $p = .211$, $\eta^2_p = .013$, $BF_{incl} = 1595.18$), region and group ($F(1,116) = 0.27$, $p = .605$, $\eta^2_p = .002$, $BF_{incl} = 9.32$), as well as between region, condition, and group ($F(1,116) = 0.21$, $p = .651$, $\eta^2_p = .002$, $BF_{incl} = 2867.18$) were not significant, although Bayes Factor indicated in favor of including them in the model. The effect of group was not significant and Bayes Factor indicated against including it in the model ($F(1,116) = 0.18$, $p = .673$, $\eta^2_p = .002$, $BF_{incl} < 0.00001$). Any other interactions were not significant and Bayes Factor indicated against including them in the model or did not provide conclusive evidence for either inclusion or exclusion. Since Bayes Factor suggested the inclusion of hemisphere*group, region*group and region*condition*group interactions in the model, follow-up Bayesian *t*-tests were conducted to verify whether this was driven by differences between control and dyslexic groups. The results, however, supported the null hypothesis both in the left ($M_{DYS} = -10.78$, $SD_{DYS} = 0.38$, $M_{CON} = -10.80$, $SD_{CON} = 0.36$, $BF_{10} = 0.20$) and right hemisphere ($M_{DYS} = -10.83$, $SD_{DYS} = 0.32$, $M_{CON} = -10.87$, $SD_{CON} = 0.36$, $BF_{10} = 0.24$) as well as in the frontal ($M_{DYS} = -10.68$, $SD_{DYS} = 0.34$, $M_{CON} = -10.71$, $SD_{CON} = 0.34$, $BF_{10} = 0.21$) and temporal regions (M_{DYS} = -10.92, SD_{DYS} = 0.36, M_{CON} = -10.96, SD_{CON} = 0.38, BF_{10} = 0.22). Similarly, results for the region*condition*group interaction, supported the null hypothesis both in frontal (M_{DYS} = -10.75, SD_{DYS} = 0.31, M_{CON} = -10.77, SD_{CON} = 0.32, BF_{10} = 0.21) and temporal electrodes at rest (M_{DYS} = -10.98, SD_{DYS} = 0.34, M_{CON} = -11.01, SD_{CON} = 0.36, BF_{10} = 0.22) as well as in frontal (M_{DYS} = -10.61, SD_{DYS} = 0.37, M_{CON} = -10.64, SD_{CON} = 0.37, BF_{10} = 0.21) and temporal electrodes during the language task (M_{DYS} = -10.87, SD_{DYS} = 0.39, M_{CON} = -10.90, SD_{CON} = 0.41, BF_{10} = 0.22).

Parieto-occipital electrodes

There were significant effects of hemisphere ($F(1,116) = 15.20$, $p < .001$, $\eta^2_p = .116$, $BF_{incl} > 10000$) and condition ($F(1,116) = 8.70$, $p = .004$, $\eta^2_p = .070$, $BF_{incl} > 10000$). For the main effect of hemisphere, post-hoc comparison revealed that the offset was lower in the left ($M = -11.19$, $SD = 0.52$) than in the right hemisphere ($M = -10.73$, $SD = 0.27$, $p_{corrected} < .001$), while for the main effect of condition, post-hoc comparison indicated that the offset was lower at rest ($M = -11.03$, $SD = 0.35$) compared to the language task ($M = -10.90$, $SD = 0.39$, $p_{corrected} < .001$). The interaction between condition and hemisphere was not significant, however Bayes Factor indicated in favor of including it in the model ($F(1,116) = 0.13$, $p = .725$, $\eta^2_p = .001$, $BF_{incl} = 31.62$). The effect of group was not significant and Bayes Factor indicated against including it in the model ($F(1,116) = 0.08$, $p = .781$, $\eta^2_p = .001$, $BF_{incl} = 0.04$). Any other effects or interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

7.2.3. Beta power (14-30 Hz) aperiodic-adjusted

Frontal and temporal electrodes

For these analyses the sample size was 117 (DYS $n = 57$, CON $n = 60$) since beta peak was not detected in the left frontal electrodes during the task in 2 participants.

The results indicated significant effects of condition ($F(1,115) = 8.58$, $p = .004$, $\eta^2_p = .069$, $BF_{incl} = 5.82$), region ($F(1,115) = 10.98$, $p = .001$, $\eta^2_p = .087$, $BF_{incl} = 23.71$), and hemisphere ($F(1,115) = 12.08$, $p < .001$, $\eta^2_p = .095$, $BF_{incl} = 23.91$). For the main effect of condition, post-hoc comparison revealed that the beta power was greater during the language task ($M = 0.53$, $SD = 0.22$) compared to the resting state ($M = 0.50$, $SD = 0.19$, $p_{corrected} = .004$), for the main effect of region, post-hoc comparison indicated that the beta power was greater in the temporal ($M = 0.52$, $SD = 0.21$) than in the frontal region ($M = 0.50$, $SD = 0.19$, $p_{\text{corrected}} = .001$), while for the main effect of hemisphere, post-hoc comparison revealed that the beta power was greater in the right ($M = 0.52$, $SD = 0.20$) compared to the left hemisphere ($M = 0.51$, $SD = 0.20$, $p_{\text{corrected}} < .001$). Furthermore, there was a significant interaction between condition and region ($F(1,115) = 12.68$, $p < .001$, $\eta^2_p = .099$, $BF_{\text{incl}} = 55.26$) with greater beta power during the language task than at rest, which was significant in the temporal ($M_{\text{rest}} = 0.50$, $SD_{\text{rest}} = 0.20$, $M_{\text{task}} = 0.55$, $SD_{\text{task}} = 0.24$, $p_{\text{corrected}} < .001$), while not in the frontal region ($M_{\text{rest}} = 0.49$, $SD_{\text{rest}} = 0.18$, $M_{\text{task}} = 0.51$, $SD_{\text{task}} = 0.22$, $p_{\text{corrected}} = .077$). Also, greater beta power in the temporal than in the frontal region was significant during the language task ($p_{\text{corrected}} < .001$), while not at rest ($p_{\text{corrected}} = .283$). The effect of group was not significant and Bayes Factor indicated against including it in the model ($F(1,115) = 0.05$, $p = .817$, $\eta^2_p = .000$, $BF_{\text{incl}} < 0.00001$). Any other interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

Parieto-occipital electrodes

There were significant effects of hemisphere ($F(1,117) = 18.74$, $p < .001$, $\eta^2_p = .138$, $BF_{\text{incl}} = 612.30$) and condition ($F(1,117) = 24.05$, $p < .001$, $\eta^2_p = .170$, $BF_{\text{incl}} = 4545.40$). For the main effect of hemisphere, post-hoc comparison revealed that the beta power was greater in the right ($M = 0.56$, $SD = 0.19$) than in the left hemisphere ($M = 0.53$, $SD = 0.18$, $p_{\text{corrected}} < .001$), while for the main effect of condition, post-hoc comparison indicated that the beta power was greater during the language task ($M = 0.57$, $SD = 0.21$) compared to the resting state ($M = 0.51$, $SD = 0.18$, $p_{\text{corrected}} < .001$). The effect of group was not significant; however, Bayes Factor did not provide conclusive evidence for either inclusion or exclusion ($F(1,117) = 0.06$, $p = .841$, $\eta^2_p = .000$, $BF_{\text{incl}} = 0.55$). Any other interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

Table 11. *Descriptive statistics for the EEG results separately for the groups.*

	DYS		CON	
	M	*SD*	*M*	*SD*
EEG resting state[a]				
Exponent mean (rest)	1.54	0.14	1.54	0.18
Exponent left IFG (rest)	1.54	0.16	1.53	0.18
Exponent left STS (rest)	1.50	0.18	1.47	0.22
Exponent right IFG (rest)	1.54	0.15	1.54	0.18

	DYS		CON	
	M	*SD*	*M*	*SD*
Exponent right STS (rest)	1.48	0.18	1.45	0.22
Exponent left parietal (rest)	1.46	0.18	1.46	0.24
Exponent right parietal (rest)	1.53	0.18	1.52	0.23
Offset mean (rest)	-10.80	0.19	-10.80	0.24
Offset left IFG (rest)	-10.72	0.34	-10.74	0.33
Offset left STS (rest)	-10.97	0.38	-10.98	0.37
Offset right IFG (rest)	-10.79	0.29	-10.81	0.32
Offset right STS (rest)	-10.99	0.31	-11.04	0.36
Offset left parietal (rest)	-11.28	0.47	-11.22	0.52
Offset right parietal (rest)	-10.80	0.23	-10.80	0.28
Beta power left IFG (rest)	0.48	0.18	0.48	0.20
Beta power left STS (rest)	0.49	0.19	0.48	0.21
Beta power right IFG (rest)	0.49	0.18	0.50	0.19
Beta power right STS (rest)	0.51	0.20	0.50	0.21
Beta power left parietal (rest)	0.49	0.18	0.50	0.20
Beta power right parietal (rest)	0.53	0.19	0.52	0.19
EEG language task[a]				
Exponent mean (task)	1.55	0.15	1.56	0.18
Exponent left IFG (task)	1.55	0.16	1.55	0.19
Exponent left STS (task)	1.50	0.20	1.47	0.21
Exponent right IFG (task)	1.54	0.17	1.55	0.19
Exponent right STS (task)	1.47	0.19	1.45	0.22
Exponent left parietal (task)	1.47	0.20	1.46	0.24
Exponent right parietal (task)	1.54	0.18	1.52	0.22
Offset mean (task)	-10.67	0.25	-10.67	0.28
Offset left IFG (task)	-10.58	0.39	-10.60	0.37
Offset left STS (task)	-10.86	0.44	-10.87	0.42
Offset right IFG (task)	-10.65	0.36	-10.68	0.37
Offset right STS (task)	-10.88	0.36	-10.94	0.41
Offset left parietal (task)	-11.15	0.52	-11.13	0.57
Offset right parietal (task)	-10.66	0.27	-10.67	0.31
Beta power left IFG (task)[b]	0.50	0.23	0.51	0.21
Beta power left STS (task)	0.54	0.24	0.53	0.23
Beta power right IFG (task)	0.51	0.23	0.52	0.21
Beta power right STS (task)	0.55	0.26	0.55	0.23
Beta power left parietal (task)	0.55	0.23	0.57	0.19
Beta power right parietal (task)	0.58	0.24	0.60	0.20

Note. DYS – dyslexic group; CON – control group; mean – values averaged across all electrodes;
left IFG – values averaged across 3 electrodes corresponding to the left inferior frontal gyrus (F7, FT7, FC5);
left STS – values averaged across 3 electrodes corresponding to the left superior temporal sulcus (T7, TP7, TP9);
right IFG – values averaged across 3 electrodes corresponding to the right inferior frontal gyrus (F8, FT8, FC6);
right STS – values averaged across 3 electrodes corresponding to the right superior temporal sulcus (T8, TP8, TP10); left parietal – values averaged across 3 left parieto-occipital electrodes (PO7, PO3, O1);
right parietal – values averaged across 3 right parieto-occipital electrodes (PO8, PO4, O2);
[a]$n = 119$ (DYS $n = 59$, CON $n = 60$); [b]$n = 117$ (DYS $n = 57$, CON $n = 60$)

7.3. Relationships between E/I balance biomarkers and reading-related skills

The neural noise hypothesis of dyslexia suggests that neural noise disrupts: 1) phonological awareness, 2) lexical access and generalization, and 3) multisensory integration (Hancock et al., 2017). Therefore, in the next step of the analysis I examined correlations between these variables and various EEG E/I balance measures (exponent, offset, and beta power). To reduce the number of correlations, in addition to values averaged across all electrodes, only measures from the left STS were included, as the neural noise hypothesis predicts significant correlations between Glu/GABA ratio and phonological awareness specifically in the left superior temporal regions (Hancock et al., 2017).

As a composite score for phonological awareness, the averaged z-scores measures from phoneme deletion and spoonerism tasks (phonemes and syllables) was calculated. Similarly, the composite score for lexical access and generalization was derived by averaging z-scores from the objects, colors, letters, and digits subtests of the RAN task. For the composite score of reading, averaged z-scores from the number of words and pseudowords read per minute and the outcome time for the reading comprehension task was calculated. To ensure consistency across all z-scored measures, raw time scores from the RAN and reading comprehension tasks were converted to items/time scores, with higher values reflecting better performance in all measures. The multisensory integration score was derived from the RTE task (the AUC measure, described in detail in Section 3.3.2. of this thesis), with higher values reflecting a greater magnitude of multisensory integration.

Zero-order correlations between variables are presented in Table 12. Phonological awareness was positively correlated with beta power in the left STS both at rest ($r = .22$, $p = .017$, $BF_{10} = 1.96$) and during the language task ($r = .21$, $p = .021$, $BF_{10} = 1.61$). Nevertheless, Bayes Factor indicated a lack of evidence to support either the alternative or the null hypothesis pointing to weak relationships between these variables. In terms of associations between reading-related cognitive skills, reading was positively correlated with phonological awareness ($r = .62$, $p < .001$, $BF_{10} > 10000$), RAN ($r = .73$, $p < .001$, $BF_{10} > 10000$) and multisensory integration ($r = .24$, $p = .028$, $BF_{10} = 1.44$), although in the latter case Bayes Factor did not provide evidence for either the alternative or null hypothesis. Moreover, phonological awareness was positively correlated with RAN ($r = .50$, $p < .001$, $BF_{10} > 10000$) and multisensory integration ($r = .33$, $p = .002$, BF$_{10}$ = 16.94). In contrast, RAN and multisensory integration were not correlated (r = .08, p = .486, BF$_{10}$ = 0.17).

Table 12. *Zero-order correlations between reading, phonological awareness, rapid automatized naming (RAN), multisensory integration and EEG biomarkers of excitatory/inhibitory balance.*

Variable	1. *r* (BF$_{10}$)	2.	3.	4.
EEG resting state				
1. Reading	–			
2. Phonological awareness	.62***$_{a}$ (>10000)	–		
3. RAN	.73***$_{a}$ (>10000)	.50***$_{a}$ (>10000)	–	
4. Multisensory integration	.24*$_{b}$ (1.44)	.33**$_{b}$ (16.94)	.08$_{b}$ (0.17)	–
5. Exponent mean (rest)	-.13$_{a}$ (0.30)	.05$_{a}$ (0.13)	-.08$_{a}$ (0.17)	-.05$_{b}$ (0.15)
6. Offset mean (rest)	-.03$_{a}$ (0.12)	.04$_{a}$ (0.13)	-.02$_{a}$ (0.12)	-.01$_{b}$ (0.14)
7. Exponent left STS (rest)	-.14$_{a}$ (0.37)	-.01$_{a}$ (0.12)	-.07$_{a}$ (0.16)	-.15$_{b}$ (0.33)
8. Offset left STS (rest)	.03$_{a}$ (0.12)	.09$_{a}$ (0.18)	.03$_{a}$ (0.12)	-.07$_{b}$ (0.17)
9. Beta power left STS (rest)	.03$_{a}$ (0.12)	.22*$_{a}$ (1.96)	-.04$_{a}$ (0.12)	.04$_{b}$ (0.14)
EEG language task				
5. Exponent mean (task)	-.13$_{a}$ (0.32)	.06$_{a}$ (0.14)	-.14$_{a}$ (0.34)	-.09$_{b}$ (0.19)
6. Offset mean (task)	-.05$_{a}$ (0.13)	.04$_{a}$ (0.12)	-.05$_{a}$ (0.13)	-.01$_{b}$ (0.13)
7. Exponent left STS (task)	-.11$_{a}$ (0.23)	.01$_{a}$ (0.12)	-.11$_{a}$ (0.24)	-.17$_{b}$ (0.48)
8. Offset left STS (task)	.04$_{a}$ (0.12)	.09$_{a}$ (0.18)	.01$_{a}$ (0.12)	-.07$_{b}$ (0.16)
9. Beta power left STS (task)	.05$_{a}$ (0.13)	.21*$_{a}$ (1.61)	.02$_{a}$ (0.12)	.11$_{b}$ (0.22)

Note. r – Pearson's correlation coefficient; BF$_{10}$ – Bayes Factor indicating ratio of the likelihood of an alternative hypothesis (H1) to a null hypothesis (H0); mean – values averaged across all electrodes; left STS – values averaged across 3 electrodes corresponding to the left superior temporal sulcus (T7, TP7, TP9). ***p < .001 (uncorrected); **p < .01 (uncorrected); *p < .05 (uncorrected);
^{a}n = 119; ^{b}n = 87

Next, these correlations were reanalyzed while controlling for age-related effects. Age showed a positive correlation with multisensory integration (r = .38, p < .001,

$BF_{10} = 87.98$), as well as with the composite scores for reading ($r = .22$, $p = .014$, $BF_{10} = 2.24$) and phonological awareness ($r = .21$, $p = .021$, $BF_{10} = 1.59$). However, no significant correlation was observed between age and the composite score for RAN ($r = .13$, $p = .151$, $BF_{10} = 0.32$). Therefore, the influence of age was controlled by regressing it out of the multisensory integration, reading, and phonological awareness scores. Similarly, the effect of age was regressed out from exponents and offsets and subsequently partial and semi-partial correlations between the variables were conducted (see Table 13).

When the effect of age was controlled, phonological awareness was positively associated with the offset in the left STS at rest ($r = .18$, $p = .049$, $BF_{10} = 0.77$) and with beta power in the left STS both at rest ($r = .23$, $p = .011$, $BF_{10} = 2.73$; see Figure 12A) and during the language task ($r = .23$, $p = .011$, $BF_{10} = 2.84$; Figure 12B). However, Bayes Factor indicated a lack of evidence to support either the alternative or the null hypothesis pointing to weak relationships between these variables. Regarding associations between reading-related cognitive skills when controlling for the effect of age, reading was positively correlated with phonological awareness ($r = .60$, $p < .001$, $BF_{10} > 10000$; Figure 12C) and RAN ($r = .71$, $p < .001$, $BF_{10} > 10000$). In contrast to zero-order correlations, relationship between reading and multisensory integration was not significant and Bayes Factor did not provide evidence for either alternative or null hypothesis ($r = .16$, $p = .130$, $BF_{10} = 0.41$). Phonological awareness was positively correlated with RAN ($r = .48$, $p < .001$, $BF_{10} > 10000$) and multisensory integration ($r = .25$, $p = .018$, $BF_{10} = 2.09$) although in the latter case Bayes Factor did not provide evidence for either the alternative or null hypothesis. Again, RAN and multisensory integration were not correlated ($r = .02$, $p = .873$, $BF_{10} = 0.14$).

Table 13. *Partial and semi-partial correlations between reading, phonological awareness, rapid automatized naming (RAN), multisensory integration and EEG biomarkers of excitatory/inhibitory balance. The effect of age was regressed out from reading, phonological awareness, multisensory integration, exponents and offsets.*

Variable	1. *r* (BF$_{10}$)	2.	3.	4.
EEG resting state				
1. Reading	–			
2. Phonological awareness	.60***$_{a}$ (>10000)	–		
3. RAN	.71***$_{a}$ (>10000)	.48***$_{a}$ (>10000)	–	
4. Multisensory integration	.16$_{b}$ (0.41)	.25*$_{b}$ (2.09)	.02$_{b}$ (0.14)	–
5. Exponent mean (rest)	-.08$_{a}$ (0.17)	.10$_{a}$ (0.20)	-.06$_{a}$ (0.14)	.02$_{b}$ (0.14)
6. Offset mean (rest)	.06$_{a}$ (0.14)	.14$_{a}$ (0.35)	.03$_{a}$ (0.12)	.16$_{b}$ (0.38)
7. Exponent left STS (rest)	-.08$_{a}$ (0.16)	.06$_{a}$ (0.14)	-.04$_{a}$ (0.12)	-.04$_{b}$ (0.14)
8. Offset left STS (rest)	.12$_{a}$ (0.25)	.18*$_{a}$ (0.77)	.08$_{a}$ (0.17)	.08$_{b}$ (0.18)
9. Beta power left STS (rest)	.04$_{a}$ (0.13)	.23*$_{a}$ (2.73)	-.04$_{a}$ (0.12)	.05$_{b}$ (0.15)
EEG language task				
5. Exponent mean (task)	-.07$_{a}$ (0.16)	.13$_{a}$ (0.30)	-.10$_{a}$ (0.21)	.01$_{b}$ (0.14)
6. Offset mean (task)	.05$_{a}$ (0.13)	.14$_{a}$ (0.34)	.01$_{a}$ (0.12)	.18$_{b}$ (0.50)
7. Exponent left STS (task)	-.03$_{a}$ (0.12)	.09$_{a}$ (0.18)	-.07$_{a}$ (0.15)	-.04$_{b}$ (0.14)
8. Offset left STS (task)	.13$_{a}$ (0.28)	.18$_{a}$ (0.71)	.07$_{a}$ (0.15)	.09$_{b}$ (0.19)
9. Beta power left STS (task)	.07$_{a}$ (0.15)	.23*$_{a}$ (2.84)	.02$_{a}$ (0.12)	.15$_{b}$ (0.33)

Note. r – Pearson's correlation coefficient; BF$_{10}$ – Bayes Factor indicating ratio of the likelihood of an alternative hypothesis (H1) to a null hypothesis (H0); mean – values averaged across all electrodes; left STS – values averaged across 3 electrodes corresponding to the left superior temporal sulcus (T7, TP7, TP9); ***$p < .001$ (uncorrected); *$p < .05$ (uncorrected);
$^{a}n = 119$; $^{b}n = 87$

Given the observed correlation between beta power and phonological awareness irrespective of condition, and the prediction that neural noise hinders reading by impairing phonological awareness (Hancock et al., 2017), this relationship was further investigated using a mediation model. Since phonological awareness was correlated with beta power in the left STS both at rest and during the language task, the beta power outcomes from these conditions were averaged before conducting the mediation analysis. The analysis was performed using the PROCESS macro v4.2 (Hayes, 2017) in IBM SPSS Statistics v29, employing model 4 (simple mediation) with 5000 bootstrap samples to assess the significance of the indirect effect. Age, which correlated with both phonological awareness and reading, was included as a covariate.

The results showed significant effects of beta power in the left STS (b = .96, $t(116)$ = 2.71, p = .008, BF_{incl} = 7.53) and age (b = .06, $t(116)$ = 2.55, p = .012, BF_{incl} = 5.98) on phonological awareness. Phonological awareness also significantly predicted reading scores (b = .69, $t(115)$ = 8.16, p < .001, BF_{incl} > 10000). However, neither beta power (b = −.42, $t(115)$ = −1.25, p = .213, BF_{incl} = 0.52) nor age (b = .03, $t(115)$ = 1.18, p = .241, BF_{incl} = 0.49) had a significant effect on reading when controlling for phonological awareness. The indirect effect of beta power on reading through phonological awareness was significant (b = .66, SE = .24, 95%CI = [.24,1.18]), while the total effect of beta power on reading was not (b = .24, $t(116)$ = 0.61, p = .546, BF_{incl} = 0.41). The mediation analysis results are illustrated in Figure 12D.

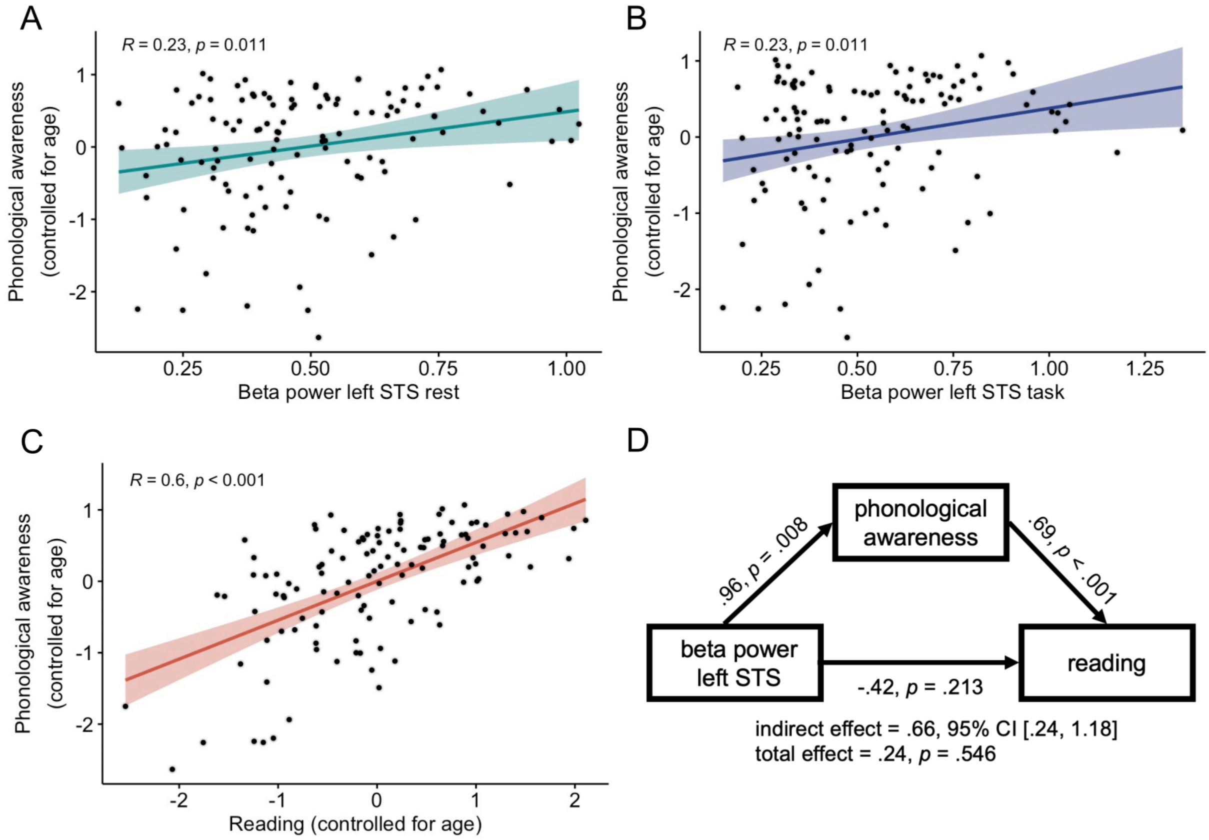

Figure 12. *(A) Semi-partial correlations between phonological awareness controlling for age and beta power (in the left STS electrodes) at rest and **(B)** during the language task. **(C)** Partial correlation between phonological awareness and reading controlling for age. **(D)** Mediation analysis results. Unstandardized b regression coefficients are presented. Age was included in the analysis as a covariate. 95% CI – 95% confidence intervals; left STS – values averaged across 3 electrodes corresponding to the left superior temporal sulcus (T7, TP7, TP9).*

8. NEURAL NOISE – DISCUSSION

The results reported in this section addressed the second aim of the thesis: validation the neural noise hypothesis of dyslexia (Hancock et al., 2017) using both periodic (beta and gamma oscillations) and aperiodic (1/f signal) EEG E/I balance biomarkers. Consistent with the hypothesis's prediction of increased neural noise in dyslexia, I expected to observe flatter slopes of the 1/f signal (lower exponent and offset), as well as lower beta and gamma power in participants with dyslexia. Furthermore, increased neural noise was anticipated to correlate with worse outcomes in phonological awareness, RAN, and multisensory integration tasks.

At the behavioral level, participants with dyslexia performed worse on most reading and reading-related tasks, including phonological awareness and RAN, as suggested by the neural noise hypothesis. The only exception was the visual attention task, where no significant group differences were observed in the number of errors or omissions. This pattern is consistent with the findings from the analysis of the 88 participants reported in the previous section of this thesis.

Regarding the aperiodic (exponent and offset) EEG biomarkers, the current results did not provide evidence for any between-group differences. In most models, the Bayes Factor neither supported nor refuted the inclusion of the group effect. However, in analyses of the offset, the results supported excluding the group factor from the model for both frontal-temporal and parieto-occipital regions. These findings contradict previous research on Italian-speaking participants, which reported reduced exponent and offset values in the dyslexic group within the parieto-occipital region at rest (Turri et al., 2023). Notably, although the current study included twice as many participants and employed a longer data acquisition period compared to the study by Turri et al. (2023), no group differences were identified, even when analyzing the same cluster of parieto-occipital electrodes. Both studies included participants of similar ages, with the primary methodological discrepancy being the acquisition of resting-state EEG recordings with eyes open in the present study, compared to both eyes-open and eyes-closed conditions in Turri et al. (2023). However, this difference does not fully explain the absence of group differences observed here, as Turri and colleagues (2023) reported lower exponent and offset values in the dyslexic group irrespective of condition. These contrasting findings underscore the importance of accounting for potential effect size inflation in studies with smaller sample sizes.

Although differences in exponent have been associated with other neurodevelopmental disorders, such as ADHD (Pertermann et al., 2019; Robertson et al., 2019; Ostlund et al., 2021) and ASD with concurrent decline in IQ level (Manyukhina et al., 2022), our findings suggest that this does not apply to dyslexia. Furthermore, given the frequent co-occurrence of dyslexia and ADHD (Germanò et al., 2010), increased neural noise could represent a shared mechanism between the two disorders. However, participants with a comorbid ADHD diagnosis were excluded from the current study, suggesting that the EEG spectral exponent cannot serve as a biomarker for dyslexia alone. Notably, the study by Turri et al. (2023) did not specify similar exclusion criteria, raising the possibility that their positive findings in dyslexia may have been influenced by undetected ADHD comorbidity. Also, since previous research on ADHD has provided contrasting findings, with some studies indicating a lower (Pertermann et al., 2019; Ostlund et al., 2021) and others reporting a higher exponent (Robertson et al., 2019), further research into aperiodic measures across different neurodevelopmental disorders is still needed.

Regarding the aperiodic-adjusted oscillatory EEG activity, the Bayes Factor for beta power (14-30 Hz) analysis in frontal and temporal regions supported excluding the group factor from the model, while results in the parieto-occipital region were inconclusive. Similar non-significant group differences in beta power at rest have been reported in prior studies that did not adjust for aperiodic components (Babiloni et al., 2012; Fraga González et al., 2018; Xue et al., 2020). However, the current findings again contrast with the work of Turri et al. (2023), which identified reduced aperiodic-adjusted beta power (15-25 Hz) in the dyslexic group. Regarding beta power during task performance, the present results also diverge from earlier studies that reported either reduced (Spironelli et al., 2008) or elevated (Rippon & Brunswick, 2000) beta activity in individuals with dyslexia. Nevertheless, these studies utilized phonological tasks, did not adjust for aperiodic activity, and recruited children’s samples, which limits the direct comparability of findings.

Notably, analysis of gamma oscillations could not be performed, as the gamma peak was not detected above the aperiodic component in most participants. It is crucial to separate the aperiodic and periodic components of the EEG spectrum to accurately assess "true" gamma oscillations, given the 1/f characteristics of the power spectrum. However, this approach is not yet widely adopted in electrophysiology research (Hudson & Jones, 2022). In fact, previous studies examining gamma activity in dyslexia (Babiloni et al., 2012; Lasnick et al., 2023; Rufener & Zaehle, 2021) did not account for the aperiodic background activity. Theta oscillations were not analyzed for the same reason, as they often fail to meet the criteria for an oscillatory component, lacking a distinct peak in the power spectrum (Klimesch, 1999). Moreover, research on developmental changes in periodic and aperiodic components suggests that theta oscillations in older individuals are predominantly observed at frontal midline electrodes (Cellier et al., 2021). These electrodes were not included in the current study's analyses, since theta oscillations were not the primary focus of the study.

Although beta power was the main periodic measure of interest due to its prior identification as an E/I balance biomarker, exploratory analyses were also conducted for beta center frequency and bandwidth (see Supplementary Material). However, results for these parameters similarly showed no evidence of differences between the dyslexic and control groups. Likewise, exploratory analyses of alpha oscillations revealed no group differences. Overall, these findings suggest that none of the analyzed power spectrum measures effectively distinguished participants with dyslexia from controls in this study. Previous research on alpha oscillations has also yielded mixed results, with some studies reporting a decrease (Ackerman et al., 1994; Babiloni et al., 2012), others an increase (Klimesch et al., 2001), and some non-significant differences in alpha power in dyslexia (Papagiannopoulou & Lagopoulos, 2016; Turri et al., 2023). Similar to the mixed results on beta oscillations, these studies differed in tasks and analytical approaches, which could account for the heterogeneity of findings.

Importantly, in certain instances, Bayesian and frequentist statistical methods yielded conflicting results regarding the inclusion of non-significant effects. This divergence was observed in more complex ANOVA models but not in *t*-tests or correlation analyses. Notably, Bayesian ANOVA estimates have been reported to exhibit considerable variability across repetitions of the exact same analyses (Pfister, 2021), highlighting the need for cautious interpretation. To obtain more stable estimates, Pfister (2021) recommends simplifying complex ANOVA models into Bayesian *t*-tests. Accordingly, follow-up Bayesian *t*-tests were conducted in all cases where the Bayes Factor supported the inclusion of non-significant interactions involving the group factor. These follow-up analyses consistently demonstrated no differences between the dyslexic and control groups. Another potential explanation for the discrepancies between Bayesian and frequentist approaches lies in the frequentist ANOVA's inclusion of interactions between covariates and within-subject effects. These interactions were omitted in

Bayesian ANOVA models to align with the recommendation for simpler models (Pfister, 2021).

Regardless of dyslexia status, age was negatively correlated with both the exponent and offset. This finding aligns with prior studies (Cellier et al., 2021; McSweeney et al., 2021; Schaworonkow & Voytek, 2021; Voytek et al., 2015) that support the idea of maturational changes in the aperiodic components, consistent with an increased E/I ratio with age. Additionally, a significant difference in offset was identified between conditions, with lower offset values during rest compared to the language task. However, a similar pattern was not observed for the exponent. Condition-dependent changes in offset have previously been reported, e.g., between eyes-open and eyes-closed resting states (Turri et al., 2023) or between passive and active auditory tasks (Gyurkovics et al., 2022). While the exponent indicates the steepness of the EEG power spectrum, the offset represents a uniform shift in power across frequencies (Donoghue et al., 2020). The observed difference in offset between conditions aligns with increases in alpha (see Supplementary Material) and beta power during the language task, suggesting enhanced activity in both broadband (offset) and narrowband (alpha and beta oscillations) frequency ranges during task performance. The condition-dependent changes in oscillatory activity are also in line with previous studies that have demonstrated differences in alpha and beta power during various tasks (e.g., Benwell et al., 2019; Leske et al., 2014; Stokić et al., 2015) and indicate that differences in oscillations persist even after controlling for aperiodic activity.

Next, pathways proposed by the neural noise hypothesis of dyslexia were investigated. The hypothesis suggests that increased neural noise in perisylvian regions may affect reading through deficits in phonological awareness, lexical access and generalization, and multisensory integration (Hancock et al., 2017). When controlling for age, phonological awareness was found to be positively correlated with the offset in the left STS during rest and with beta power in the left STS both at rest and during the spoken language task. However, the Bayes Factor did not conclusively support either the alternative or null hypothesis, indicating that these associations are relatively weak. Previously, Turri and colleagues (2023) also identified significant relationships between offset and word reading speed as well as between beta power and reading errors in the dyslexic group. However, they did not test possible mediating relationships including cognitive skills proposed by the neural noise hypothesis. Here, based on the hypothesis's prediction of a causal link between these variables, a mediation model involving beta power, phonological awareness, and reading skills was further explored. The results indicated a positive indirect effect of beta power in the left STS on reading through phonological awareness, while both the direct effect (accounting for phonological awareness and age) and the total effect (when phonological awareness was not accounted for) were not significant. This finding is notable, given that participants with dyslexia performed worse in phonological awareness and reading tasks, yet no between-group differences in beta power were observed. Further longitudinal research is needed to confirm any causal relationships among these variables, due to the cross-sectional nature of the current study.

Overall, these findings suggest that the neural noise hypothesis (Hancock et al., 2017) does not sufficiently explain the reduced reading skills observed in dyslexia. No differences between groups were found in any EEG measures of neural noise, whereas, at the behavioral level, the dyslexic group performed worse in most reading and reading-related tasks. While this study focused on EEG E/I balance biomarkers, previous MRS studies examining Glu and GABA concentrations in dyslexia (Del Tufo et al., 2018; Horowitz-Kraus et al., 2018; Kossowski et al., 2019; Pugh et al., 2014) have also yielded mixed evidence for the neural noise hypothesis. However, since the current sample consisted of adolescents and young adults, and EEG data were collected at rest and during a spoken language task, future studies should investigate younger populations and include a broader range of tasks during EEG recordings, such as reading and phonological tasks, to more thoroughly evaluate potential E/I balance alterations in dyslexia.

Importantly, although the current findings do not support the idea that differences in E/I balance underlie neural noise in dyslexia, other mechanisms contributing to reduced neural synchronization and disrupted sensory encoding, also proposed by the hypothesis, cannot be ruled out. In this regard, there are studies reporting worse cortical entrainment to auditory stimuli reflecting syllabic (Leong & Goswami, 2014), prosodic (Molinaro et al., 2016) and phonemic rates of speech in dyslexia (Lehongre et al., 2011; Marchesotti et al., 2020; Van Hirtum et al., 2019). Additionally, previous research has reported increased trial-to-trial variability in neural responses among individuals with dyslexia (Centanni et al., 2022) or poor readers (Hornickel & Kraus, 2013), and its links with dyslexia-related risk genes (Centanni et al., 2018; Neef et al., 2017). However, this variability has been observed only in some participants (Centanni et al., 2018), was limited to certain experimental conditions (Centanni et al., 2022), or was localized in different brain regions, such as the left auditory cortex (Centanni et al., 2018), left SMG

(Centanni et al., 2022) or the brainstem (Hornickel & Kraus, 2013). Moreover, one study using behavioral and fMRI data did not observe increased variability in dyslexia (Tan et al., 2022) highlighting the importance of exploring alternative neural mechanisms associated with dyslexia.

In conclusion, the current results do not support the neural noise hypothesis of dyslexia (Hancock et al., 2017), as no differences between dyslexic and control groups were identified in any EEG E/I balance biomarkers (exponent, offset, or beta power). Interestingly, despite the lack of group differences in beta power, a positive mediating relationship was observed between beta power in the left STS, phonological awareness, and reading. These findings suggest the need for further investigation into the role of E/I balance in reading skills through longitudinal studies, as well as the necessity of identifying other biomarkers underlying dyslexia.

9. GENERAL DISCUSSION

The results reported in the current thesis aimed to: 1) investigate sex-specific behavioral and neural effects in multisensory integration in dyslexia and 2) validate the neural noise hypothesis, which posits an imbalance between excitatory and inhibitory neural activity in dyslexia. Although the neural noise hypothesis predicted deficits in multisensory integration (Hancock et al., 2017), it did not suggest any differences between females and males at either the cognitive or neural level. Hence, the analysis of sex differences in multisensory integration extended beyond the direct predictions of the hypothesis, enabling a broader approach to exploring the mechanisms of dyslexia.

Regarding cognitive deficits associated with dyslexia, the current sample of adolescents and young adults with dyslexia scored lower than controls in phonological awareness, RAN, short-term and working memory, as well as in perception speed on a visual attention test with digit stimuli. The effect sizes were large for phonological and short-term/working memory tasks, while medium for RAN and perception speed. This aligns with both the phonological deficit hypothesis, which posits that reading difficulties stem from disruptions in phonological awareness, phonological recoding, and phonological memory (Snowling, 1998; Stanovich, 1988; Wagner & Torgesen, 1987), as well as the double-deficit hypothesis, which predicts deficiencies in phonological processing and RAN in dyslexia (Wolf & Bowers, 1999). Regarding effect sizes for phonological awareness and RAN, previous studies suggest that their predictive power for reading skills varies depending on orthographic transparency (Borleffs et al., 2019; Ziegler, Bertrand et al., 2010). Specifically, phonological awareness is considered a stronger predictor of reading skills in opaque languages, where the pronunciation of letters varies across words, compared to transparent languages, where given letters are almost always pronounced the same way (Borleffs et al., 2019; Ziegler, Bertrand et al., 2010). Some studies have also indicated that in more transparent languages, RAN has a greater impact on reading abilities than phonological awareness (De Jong & van der Leij, 1999; Wimmer et al., 2000). Since Polish is characterized by intermediate orthographic transparency (Schüppert et al., 2017), both phonological awareness and RAN may contribute comparably to reading skills. However, the greater effect sizes for phonological awareness than for RAN found in the present study align with previous research showing a weaker contribution of RAN than phonological awareness across five languages with different levels of orthographic transparency (Ziegler, Bertrand et al., 2010). Lower scores in the perception speed score are also in line with previous studies implying deficits in the speed of processing in dyslexia (Abbott et al., 2015; McLean et al., 2011; Stenneken et al., 2011; Stoet et al., 2007); however, may also originate from phonological deficits due to the test material (digits) mapping onto phonological codes (Hokken et al., 2023; Ziegler, Pech-Georgel et al., 2010). In contrast, no significant group differences were found in perceptual discrimination and selective attention scores, which do not support the idea that attentional deficits are a defining feature of dyslexia, as proposed by the magnocellular (Stein & Walsh, 1997) or the SAS hypotheses (Hari & Renvall, 2001).

Although both females and males with dyslexia performed worse in the above-mentioned reading-related tasks, only males with dyslexia benefited less from multisensory inputs in the RTE task with simple non-linguistic stimuli. This finding aligns with the multiple deficit model, which posits that dyslexia originates from the interaction of multiple risk factors rather than a single cause (McGrath et al., 2020; Pennington, 2006). Given that this is the first study to show such sex-specific differences in multisensory integration in dyslexia, further research is needed to corroborate these findings. In particular, investigating its developmental trajectory would be interesting. Previous studies have shown that multisensory integration develops late in humans; however, the exact age of maturation varies depending on the tasks and methods employed (Burr & Gori, 2012). For instance, audiovisual facilitation studied through motor responses in the RTE task, begins to emerge around 7 years of age but still remains immature in 10- to 11-year-old children (Barutchu et al., 2009). Similarly, at the behavioral level, multisensory effects in a spatial cueing task were absent in children aged 5 to 9; however, in 9-year-olds, such effects were detected at the electrophysiological level (Turoman et al., 2021). In contrast, when race model violations were examined in an audiovisual spatial task based on head and eye movements in infants aged 1 to 10 months, multisensory facilitation was observed between 8 and 10 months of age (Neil et al., 2006). These findings raise questions about the pace of multisensory integration development across various tasks in females and males with dyslexia. In particular, exploring the relationship between multisensory integration involving simple, non-linguistic stimuli and letter-speech sound pairings would be especially interesting in developmental studies. The mechanisms of multisensory integration appear to differ depending on the stimuli – for instance, between naturally occurring audiovisual objects, such as audiovisual speech perception, and inherently arbitrary pairings, such as letter-speech sound associations, which take years to become automated (Blomert & Froyen, 2010). Therefore, investigating the shared and distinct mechanisms of multisensory integration across linguistic and non-linguistic stimuli in males and females with dyslexia would build upon the findings of the present study.

Additionally, the relationships between multisensory integration and different reading-related cognitive skills warrant further investigation. In the present study, a positive association between behavioral facilitation in the RTE task and pseudoword reading speed was found to be significant only in males with dyslexia (as reported in the Multisensory Integration section of this thesis). However, when this measure was correlated with composite scores for reading, phonological awareness, and RAN across the entire sample (as reported in the Neural Noise section of this thesis), no significant correlation was found between multisensory integration and reading after controlling for age. In contrast, the relationship between multisensory integration and phonological awareness remained significant when the effect of age was controlled. The decision to include only one measure of pseudoword reading speed in the separate analyses by sex was based on previous studies demonstrating its consistent ability to predict reading difficulties in adults (Brèthes et al., 2022; Carioti et al., 2021; Reis et al., 2020). Moreover, findings from both Polish and English studies indicate that while phonological deficits are the most commonly observed in dyslexia, they are present in only about 50% of individuals (Dębska et al., 2022; Pennington et al., 2012). Given this, examining the co-occurrence of deficits in multisensory integration and phonological awareness at the individual level would be an interesting avenue for future research. In this study, reading and reading-related tests (including phonological ones) were used solely for group-level comparisons due to the lack of norms for adult participants, which precluded such analyses.

Moreover, differences in the neural processing of multisensory information between females and males with dyslexia were observed only in a subsample of participants matched for nonverbal IQ, suggesting that the neural correlates of these differences require further investigation. Additionally, since this study included only electrophysiological data, its reference to specific brain regions associated with the reported differences is limited due to the low spatial resolution of EEG. Previous evidence points to numerous cortical and subcortical structures involved in multisensory integration (Calvert, 2001; Choi et al., 2023). Cortical regions include the parietal cortex (superior parietal lobule, intraparietal sulcus, parieto-occipital sulcus), temporal cortex

(STS, STG), and frontal cortex (IFG, ventrolateral prefrontal cortex, orbitofrontal cortex, anterior cingulate cortex), while subcortical structures include the superior colliculus, thalamus, claustrum and insula (Calvert, 2001; Choi et al., 2023). Interestingly, although hypoactivation in the left IFG and left STS/STG is consistently observed in dyslexia (Maisog et al., 2008; Martin et al., 2016; Richlan et al., 2011; Yan et al., 2021), no evidence suggests differential activation between females and males in these structures. In contrast, some studies have shown that differences in gray matter volume in the left temporo-parietal cortex (Evans et al., 2014), white matter integrity in the left hemisphere (Gupta et al., 2024), or asymmetry of the planum temporale (Altarelli et al., 2014) are present only in males with dyslexia. Additionally, one functional study found a positive correlation between stronger left-lateralized activity in the magnocellular division of the left lateral geniculate nucleus of the thalamus during a visual task designed to target magnocellular cells (achromatic stimuli at low spatial frequency) and completion time on the RAN task in males with dyslexia (Müller-Axt et al., 2025). In contrast, this correlation was not significant in females with dyslexia. However, in the group-level analysis, no sex differences were identified in the activity of this structure, while a general difference between dyslexic and control group was found, with greater activity in the left than in the right magnocellular thalamus observed only in participants with dyslexia (Müller-Axt et al., 2025). Since none of these studies evaluated multisensory integration, the specific structures associated with the sex differences observed in the present study remain to be investigated. Alternatively, in line with the multiple pathways model of audiovisual integration (Gao et al., 2023), these differences may stem from disruptions in connectivity between sensory areas (the visual and auditory cortex), subcortical structures, and higher-order association areas rather than dysfunctions in individual regions.

The same limitation of low spatial resolution applies to the EEG E/I balance biomarkers included in the current study. The neural noise hypothesis predicts increased Glu concentrations specifically in the left superior temporal cortex in dyslexia, though other regions, including the visual cortex, have also been suggested (Hancock et al., 2017). Although the electrodes used for the reported analyses were selected based on previous studies examining the correspondence between electrodes and brain structures (Giacometti et al., 2014; Scrivener & Reader, 2022) to target regions within the brain's reading network (including the left STS), it is only an approximate measure of the source of the recorded signal. Yet, no evidence for group differences was found in any analyses, whether averaged across all electrodes, in electrodes corresponding to the left and right IFG and STS, or in the left and right parieto-occipital regions, similar to the work of Turri and colleagues (2023). Furthermore, a previous study on dyslexia that examined Glu and GABA concentrations specifically in the left superior temporal cortex using the MRS method found non-significant group differences in both children and adults (Kossowski et al., 2019), arguing against the predictions of the neural noise hypothesis. Also, mixed results for dyslexia-related effects in Glu and GABA levels have been found in regions outside the neural reading network – in the occipital cortex (Del Tufo et al., 2018; Kossowski et al., 2019; Pugh et al., 2014) and the anterior cingulate cortex (Cecil et al., 2021; Horowitz-Kraus et al., 2018; Lebel et al., 2016).

Furthermore, the EEG biomarkers reported in the present study provide only an indirect measure of the E/I balance (Ahmad et al., 2022) and the specific cellular mechanisms associated with different EEG power spectrum components still require further exploration due to previous ambiguous findings in pharmacological studies (Colombo et al., 2019; Gao et al., 2017; Muthukumaraswamy & Liley, 2018; Salvatore et al., 2024; Waschke et al., 2021). Given the observed indirect relationship between beta power in the left STS electrodes, phonological awareness, and reading, further research examining associations between beta power, MRS-derived GABA levels, and phonological skills would be valuable. Previous studies have indicated positive associations between GABA concentration in the motor/sensorimotor cortex and beta power (Cheng et al., 2017; Gaetz et al., 2011) or beta peak frequency (Baumgarten et al., 2016); however, they did not account for aperiodic components. Since there is evidence for positive correlations between aperiodic exponent and Glu (McKeon et al., 2024) or Glu/GABA ratio (van Bueren et al., 2023), a longitudinal investigation of aperiodic-adjusted beta power and GABA levels in the left STS in relation to reading-related skills would provide further insight into the current findings.

Interestingly, the original neural noise hypothesis of dyslexia has been recently refined into a model that integrates the initial propositions with the temporal sampling framework (Lasnick & Hoeft, 2024). According to this updated model, increased cortical excitability in dyslexia is thought to be associated with impaired cortical entrainment to auditory stimuli, particularly at prosodic (delta oscillations), syllabic (theta oscillations), and phonemic (gamma oscillations) rates of speech (Lasnick & Hoeft, 2024). Since the current study did not aim to assess cortical tracking of auditory stimuli, future research should explore these proposed relationships. However, since no evidence of group differences was found in any of the tested EEG E/I balance biomarkers, other sources of reduced cortical encoding should be considered. Moreover, the observed sex-specific effects in low-level multisensory integration suggest that distinct neural and cognitive pathways may contribute to dyslexia in males and females, which could be accounted for in future models of reading difficulties.

10. SUMMARY & CONCLUSIONS

To sum up, the results reported in this thesis indicate that:

- Behavioral deficits in low-level audiovisual multisensory integration are present in males with dyslexia, but not in females.

- Both females and males with dyslexia exhibit smaller differences in neural responses between multisensory and unisensory conditions in the N1 and N2 ERP components. However, in participants matched for non-verbal IQ, only males with dyslexia show a smaller difference between responses to multisensory and unisensory conditions in the N1 component of the left hemisphere.

- There is no evidence of differences between dyslexic and control groups in any of the EEG E/I balance biomarkers (exponent, offset, beta power) either at rest or during the spoken language task, which does not support the prediction of heightened cortical excitability associated with dyslexia.

- There is a positive mediating relationship between beta power in the left STS electrodes, phonological awareness, and reading, which should be further examined in longitudinal studies.

In conclusion, the present study suggests that the neural noise hypothesis (Hancock et al., 2017) does not fully explain reading difficulties. Future models should explore alternative neural mechanisms, as well as potential sex-specific pathways contributing to the emergence of dyslexia.

11. NEURAL NOISE – SUPPLEMENTARY MATERIAL

11.1. Beta (14-30 Hz) aperiodic-adjusted

11.1.1. Frontal and temporal electrodes

For these analyses the sample size was 117 (DYS $n = 57$, CON $n = 60$) since beta peak was not detected in the left frontal electrodes during the task in 2 participants.

Beta center frequency

The results indicated a significant effect of condition ($F(1,115) = 6.12$, $p = .015$, $\eta^2_p = .051$, $BF_{incl} = 2.94$) and post-hoc comparison revealed that the beta peak was at higher frequencies at rest ($M = 19.86$, $SD = 2.64$) than during the language task ($M = 19.44$, $SD = 2.48$, $p_{corrected} = .015$). An interaction between condition and region was also significant, however the Bayes Factor did not provide conclusive evidence for either inclusion or exclusion ($F(1,115) = 5.96$, $p = .016$, $\eta^2_p = .049$, $BF_{incl} = 1.52$). Post-hoc comparisons indicated that the beta peak was at higher frequencies at rest compared to the language task in the frontal region ($M_{rest} = 20.03$, $SD_{rest} = 2.79$, $M_{task} = 19.43$, $SD_{task} = 2.51$, $p_{corrected} = .002$), while this difference was not significant in the temporal region ($M_{rest} = 19.68$, $SD_{rest} = 2.76$, $M_{task} = 19.45$, $SD_{task} = 2.70$, $p_{corrected} = .207$). Moreover, during resting state condition, the beta peak was at higher frequencies in the frontal than in the temporal region ($p_{corrected} = .028$), while this difference was not significant during the language task ($p_{corrected} = .878$). The effect of group was not significant and Bayes Factor indicated against including it in the model ($F(1,115) = 0.02$, $p = .896$, $\eta^2_p = .000$, $BF_{incl} = 0.001$). Any other effects of interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

Beta bandwidth

The effect of group was not significant while Bayes Factor did not provide evidence for either inclusion or exclusion ($F(1,115) = 0.39$, $p = .532$, $\eta^2_p = .003$, $BF_{incl} = 0.60$). The interaction between group, region, and hemisphere was not significant, however Bayes Factor indicated in favor of including it in the model ($F(1,115) = 1.92$, $p = .169$, $\eta^2_p = .016$, $BF_{incl} = 389.67$). Any other effects of interactions were not significant and Bayes Factor indicated against including them in the model or did not provide conclusive evidence for either inclusion or exclusion. Since Bayesian statistics suggested the inclusion of the group*region*hemisphere interaction in the model, follow-up Bayesian *t*-tests were conducted to verify whether this was driven by differences between control and dyslexic groups. The results, however, supported the null hypothesis in both the left ($M_{\mathrm{DYS}} = 7.19$, $SD_{\mathrm{DYS}} = 2.64$, $M_{\mathrm{CON}} = 6.96$, $SD_{\mathrm{CON}} = 2.84$, $\mathrm{BF}_{10} = 0.22$) and right hemisphere in the frontal region ($M_{\mathrm{DYS}} = 6.93$, $SD_{\mathrm{DYS}} = 2.86$, $M_{\mathrm{CON}} = 7.07$, $SD_{\mathrm{CON}} = 2.80$, $\mathrm{BF}_{10} = 0.20$) as well as in the left hemisphere in the temporal region ($M_{\mathrm{DYS}} = 7.32$, $SD_{\mathrm{DYS}} = 2.57$, $M_{\mathrm{CON}} = 6.86$, $SD_{\mathrm{CON}} = 2.72$, $\mathrm{BF}_{10} = 0.29$). The results in the right hemisphere in the temporal region indicated an absence of evidence for either alternative, or null hypothesis ($M_{\mathrm{DYS}} = 7.09$, $SD_{\mathrm{DYS}} = 2.25$, $M_{\mathrm{CON}} = 6.36$, $SD_{\mathrm{CON}} = 2.61$, $\mathrm{BF}_{10} = 0.66$).

11.1.2. Parieto-occipital electrodes

Beta center frequency

There were significant interactions between group and hemisphere ($F(1,117) = 5.10$, $p = .026$, $\eta^2_p = .042$, $\mathrm{BF}_{\mathrm{incl}} = 1.74$), and between group, hemisphere, and condition ($F(1,117) = 4.15$, $p = .044$, $\eta^2_p = .034$, $\mathrm{BF}_{\mathrm{incl}} = 1.89$), however Bayes Factor did not provide conclusive evidence for either inclusion or exclusion. For the group*hemisphere interaction, post-hoc comparisons did not reveal any significant differences, while for the group*hemisphere*condition interaction, post-hoc comparisons indicated that within the dyslexic group at rest, beta peak was at lower frequencies in the right ($M = 18.51$, $SD = 1.95$) than in the left hemisphere ($M = 19.07$, $SD = 2.24$, $p_{\mathrm{corrected}} = .026$), while any other comparisons were not significant. The effect of group was not significant while Bayes Factor did not provide evidence for either inclusion or exclusion ($F(1,117) = 0.20$, $p = .659$, $\eta^2_p = .002$, $\mathrm{BF}_{\mathrm{incl}} = 0.37$). Any other effects or interactions were not significant and Bayes Factor indicated against including them in the model.

Beta bandwidth

The effect of group was not significant and Bayes Factor indicated against including it in the model ($F(1,117) = 0.02$, $p = .890$, $\eta^2_p = .000$, $\mathrm{BF}_{\mathrm{incl}} = 0.19$). Any other effects or interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

11.2. Alpha (7-14 Hz) aperiodic-adjusted

11.2.1. Frontal and temporal electrodes

For these analyses, the sample size was 112 (DYS $n = 56$, CON $n = 56$), since alpha peak was not detected in the selected electrodes in 7 participants.

Alpha power

There were significant effects of condition ($F(1,110) = 63.47$, $p < .001$, $\eta^2_p = .366$, $BF_{incl} > 10000$), hemisphere ($F(1,110) = 13.84$, $p < .001$, $\eta^2_p = .112$, $BF_{incl} = 76.81$) and region ($F(1,110) = 6.34$, $p = .013$, $\eta^2_p = .054$, $BF_{incl} = 2.98$). For the main effect of condition, post-hoc comparison revealed that the alpha power was greater during the language task ($M = 1.21$, $SD = 0.47$) compared to the resting state condition ($M = 0.99$, $SD = 0.39$, $p_{corrected} < .001$), for the main effect of hemisphere, post-hoc comparison indicated that alpha power was greater in the right ($M = 1.11$, $SD = 0.41$) than in the left hemisphere ($M = 1.09$, $SD = 0.42$, $p_{corrected} < .001$), while for the main effect of region, post-hoc comparison revealed that the alpha power was greater in the temporal ($M = 1.11$, $SD = 0.41$) than in the frontal region ($M = 1.09$, $SD = 0.42$, $p_{corrected} = .013$). Furthermore, there were significant interactions between condition, region, and group ($F(1,110) = 4.78$, $p = .031$, $\eta^2_p = .042$, $BF_{incl} = 64.84$) as well as between hemisphere and region ($F(1,110) = 4.35$, $p = .039$, $\eta^2_p = .038$, $BF_{incl} = 0.92$), however Bayes Factor did not provide evidence for either inclusion or exclusion the hemisphere*region interaction. For the condition*region*group interaction, post-hoc comparisons indicated that in both regions and in both dyslexic and control groups, alpha power was greater during the language task compared to the resting state condition (for all comparisons $p_{corrected} < .001$). Furthermore, within the control group at rest, alpha power was greater in the temporal ($M = 0.99$, $SD = 0.36$) than in the frontal region ($M = 0.95$, $SD = 0.38$, $p_{corrected} = .003$), while any other comparisons were not significant. For the hemisphere*region interaction, post-hoc comparisons indicated that greater alpha power in the temporal than in the frontal region was significant in the right ($M_{frontal} = 1.10$, $SD_{frontal} = 0.42$, $M_{temporal} = 1.13$, $SD_{temporal} = 0.40$, $p_{corrected} = .001$), while not in the left hemisphere ($M_{frontal} = 1.08$, $SD_{frontal} = 0.42$, $M_{temporal} = 1.09$, $SD_{temporal} = 0.42$, $p_{corrected} = .386$). Also, within the temporal region, greater alpha power was in the right compared to the left hemisphere ($p_{corrected} < .001$), while this difference was not significant within the frontal region ($p_{corrected} = .110$). The effect of group was not significant and

Bayes Factor indicated against including it in the model ($F(1,110) = 0.27$, $p = .607$, $\eta^2_p = .002$, $BF_{incl} = 0.02$). Any other interactions were not significant and Bayes Factor indicated against including them in the model or did not provide conclusive evidence for either inclusion or exclusion.

Alpha center frequency

The results indicated a significant effect of condition ($F(1,110) = 15.24$, $p < .001$, $\eta^2_p = .122$, $BF_{incl} = 144.27$) and post-hoc comparison revealed that the alpha peak was at lower frequencies at rest ($M = 10.51$, $SD = 0.98$) compared to the language task ($M = 10.73$, $SD = 0.94$, $p_{corrected} < .001$). There were also significant interactions between condition and hemisphere ($F(1,110) = 9.99$, $p = .002$, $\eta^2_p = .083$, $BF_{incl} = 14.42$), as well as between condition and region ($F(1,110) = 4.28$, $p = .041$, $\eta^2_p = .037$, $BF_{incl} = 0.82$), however Bayes Factor did not provide evidence for either including or excluding condition*region interaction. For the condition*hemisphere interaction, post-hoc comparisons indicated that the alpha peak was at lower frequencies at rest compared to the language task both in the left ($M_{rest} = 10.59$, $SD_{rest} = 1.04$, $M_{task} = 10.72$, $SD_{task} = 0.95$, $p_{corrected} = .048$) and in the right hemisphere ($M_{rest} = 10.42$, $SD_{rest} = 1.03$, $M_{task} = 10.75$, $SD_{task} = 0.95$, $p_{corrected} < .001$). Moreover, at rest, the alpha peak was at lower frequencies in the right than in the left hemisphere ($p_{corrected} = .008$), while this difference was not significant during the language task ($p_{corrected} = .334$). For the condition*region interaction, post-hoc comparisons indicated that alpha peak was at lower frequencies at rest than during the language task both in the temporal ($M_{rest} = 10.48$, $SD_{rest} = 0.98$, $M_{task} = 10.76$, $SD_{task} = 0.96$, $p_{corrected} < .001$) and in the frontal region ($M_{rest} = 10.53$, $SD_{rest} = 1.02$, $M_{task} = 10.71$, $SD_{task} = 0.97$, $p_{corrected} = .008$), while the difference between regions was not significant either at rest ($p_{corrected} = .128$) or during the language task ($p_{corrected} = .288$). The effect of group was not significant while Bayes Factor did not provide conclusive evidence for either inclusion or exclusion ($F(1,110) = 1.55$, $p = .216$, $\eta^2_p = .014$, $BF_{incl} = 0.70$). Any other interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

Alpha bandwidth

The results indicated a significant effect of condition ($F(1,110) = 6.21$, $p = .014$, $\eta^2_p = .053$, $BF_{incl} = 3.06$) and post-hoc comparison revealed that the alpha peak was wider at rest (M = 3.18, SD = 1.25) compared to the language task (M = 2.91, SD = 0.94, $p_{\text{corrected}}$ = .014). There was also a significant effect of region, however Bayes Factor did not provide evidence for either inclusion or exclusion (F(1,110) = 5.42, p = .022, η^2_p = .047, BF_{incl} = 1.64). Post-hoc comparison indicated that the alpha peak was wider in the temporal (M = 3.12, SD = 0.94) than in the frontal region (M = 2.97, SD = 1.04, $p_{\text{corrected}}$ = .022). There were also significant interactions between region and condition (F(1,110) = 7.33, p = .008, η^2_p = .062, BF_{incl} = 4.15) and between group and region (F(1,110) = 5.59, p = .020, η^2_p = .048, BF_{incl} = 0.38), however Bayes Factor did not provide evidence for either including or excluding group*region interaction. For the region*condition interaction, post-hoc comparisons indicated that the alpha peak was wider at rest than during the language task in the frontal region (M_{rest} = 3.18, SD_{rest} = 1.45, M_{task} = 2.77, SD_{task} = 0.99, $p_{\text{corrected}}$ = .001), while this difference was not significant in the temporal region (M_{rest} = 3.19, SD_{rest} = 1.22, M_{task} = 3.04, SD_{task} = 1.03, $p_{\text{corrected}}$ = .225). Furthermore, during the language task, the alpha peak was wider in the temporal compared to the frontal region ($p_{\text{corrected}}$ < .001), while this difference was not significant at rest ($p_{\text{corrected}}$ = .932). For the group*region interaction, post-hoc comparisons indicated that within the dyslexic group, the alpha peak was wider in the temporal than in the frontal region (M_{frontal} = 2.85, SD_{frontal} = 1.09, M_{temporal} = 3.14, SD_{temporal} = 1.01, $p_{\text{corrected}}$ = .001), while this difference was not significant within the control group (M_{frontal} = 3.10, SD_{frontal} = 0.98, M_{temporal} = 3.09, SD_{temporal} = 0.87, $p_{\text{corrected}}$ = .980). The difference between control and dyslexic groups was not significant either within the frontal ($p_{\text{corrected}}$ = .214) or the temporal region ($p_{\text{corrected}}$ = .810). The interaction between region, hemisphere, and condition was not significant, however Bayes Factor indicated in favor of including it in the model (F(1,110) = 1.54, p = .217, η^2_p = .014, BF_{incl} = 5.96). The effect of group was not significant and Bayes Factor indicated against including it in the model (F(1,110) = 0.33, p = .569, η^2_p = .003, BF_{incl} = 0.05). Any other interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

11.2.2. Parieto-occipital electrodes

For these analyses, the sample size was 117 (DYS n = 59, CON n = 58), since alpha peak was not detected in the selected electrodes in 2 participants.

Alpha power

There was a significant effect of hemisphere ($F(1,115) = 63.01$, $p < .001$, $\eta^2_p = .354$, $BF_{incl} > 10000$) and post-hoc comparison revealed that the alpha power was greater in the right ($M = 1.30$, $SD = 0.36$) than in the left hemisphere ($M = 1.22$, $SD = 0.34$, $p_{corrected} < .001$). There was also a significant effect of condition ($F(1,115) = 93.58$, $p < .001$, $\eta^2_p = .449$, $BF_{incl} > 10000$) and post-hoc comparison indicated that the alpha power was greater during the language task ($M = 1.38$, $SD = 0.36$) compared to the resting state ($M = 1.15$, $SD = 0.38$, $p_{corrected} < .001$). Moreover, there were significant interactions between group and hemisphere ($F(1,115) = 5.25$, $p = .024$, $\eta^2_p = .044$, $BF_{incl} = 2.26$), and between hemisphere and condition ($F(1,115) = 4.01$, $p = .048$, $\eta^2_p = .034$, $BF_{incl} = 1.36$), however Bayes Factor did not provide the evidence for either inclusion or exclusion. For the group*hemisphere interaction, post-hoc comparisons revealed that greater alpha power was found in the right than in the left hemisphere both within the dyslexic ($M_{left} = 1.20$, $SD_{left} = 0.35$, $M_{right} = 1.31$, $SD_{right} = 0.36$, $p_{corrected} < .001$) and the control group ($M_{left} = 1.24$, $SD_{left} = 0.33$, $M_{right} = 1.30$, $SD_{right} = 0.36$, $p_{corrected} < .001$), while the difference between the dyslexic and control group was not significant either in the left ($p_{corrected} = .497$), or the right hemisphere ($p_{corrected} = .926$). For the hemisphere*condition interaction, post-hoc comparisons indicated that the alpha power was greater in the right than in the left hemisphere both during the resting state and the language task (all comparisons $p_{corrected} < .001$), and that the alpha power was greater during the task compared to the resting state both in the left and in the right hemisphere (all comparisons $p_{corrected} < .001$). The effect of group was not significant while Bayes Factor did not provide conclusive evidence for either inclusion or exclusion ($F(1,115) = 0.08$, $p = .776$, $\eta^2_p = .001$, $BF_{incl} = 0.56$). Any other interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

Alpha center frequency

The results indicated a significant effect of condition ($F(1,115) = 92.36$, $p < .001$, $\eta^2_p = .445$, $BF_{incl} > 10000$) and post-hoc comparison revealed that the alpha peak was at lower frequencies during the resting state ($M = 10.44$, $SD = 0.95$) compared to the language task ($M = 10.87$, $SD = 0.93$, $p_{corrected} < .001$). The effect of group was not significant while Bayes Factor did not provide conclusive evidence for either inclusion or exclusion. ($F(1,115) = 2.94$, $p = .089$, $\eta^2_p = .025$, $BF_{incl} = 0.60$). Any other effects or interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

Alpha bandwidth

The effect of group was not significant; however, Bayes Factor did not provide conclusive evidence for either inclusion or exclusion ($F(1,115) = 0.01$, $p = .923$, $\eta^2_p = .000$, $BF_{incl} = 0.36$). Any other effects or interactions were not significant and Bayes Factor indicated against including them in the model or did not provide evidence for either inclusion or exclusion.

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LIST OF PUBLICATIONS

Publications reporting the results presented in this thesis:

1. **Glica, A.**, Wasilewska, K., Kossowski, B., Żygierewicz, J., & Jednoróg, K. (2024). Sex differences in low-level multisensory integration in developmental dyslexia. *Journal of Neuroscience*, *44*(3), e0944232023. https://doi.org/10.1523/JNEUROSCI.0944-23.2023
2. **Glica, A.**, Wasilewska, K., Jurkowska, J., Żygierewicz, J., Kossowski, B., & Jednoróg, K. (2025). Reevaluating the neural noise in dyslexia using biomarkers from electroencephalography and high-resolution magnetic resonance spectroscopy. *eLife*, 13, RP99920. https://doi.org/10.7554/eLife.99920.4

Other publications:

3. Draps, M., Kulesza, M., **Glica, A.**, Szymanowska, J., Lewińska, K., Żukrowska, W., & Gola, M. (2024). Emotional interference and attentional bias in compulsive sexual behaviors disorder – An fMRI study on heterosexual males. *Journal of Behavioral Addictions*, *13*(3), 791-806. https://doi.org/10.1556/2006.2024.00033
4. **Glica, A.**, Wizła, M., Gola, M., & Lewczuk, K. (2023). Hypo- or hyperfunction? Differential relationships between compulsive sexual behavior disorder facets and sexual health. *The Journal of Sexual Medicine, 20*(3), 332-345. https://doi.org/10.1093/jsxmed/qdac035
5. Lewczuk, K., Wizła, M., **Glica, A.**, & Dwulit, A. D. (2023). Compulsive sexual behavior disorder and problematic pornography use in cisgender sexual minority individuals: The associations with minority stress, social support, and sexualized drug use. *The Journal of Sex Research*, 1-15. https://doi.org/10.1080/00224499.2023.2245399
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10. **Glica, A**., Lewandowska, K., Dwulit, A. D., & Lewczuk, K. (2020). Seksualność w ujęciu międzykulturowym. In: F. Rola (Ed), *(Od)cienie seksualności w ujęciu psychologicznym* (pp. 123-139). Wydawnictwo Akademii Pedagogiki Specjalnej.
11. Marchlewska, M., Czarnecka, M., Molenda, Z., Lewczuk, K., Krysztofiak, M., **Glica, A**., & Kobylińska, D. (2019). Trzecioosobowe wizualizacje własnej przeszłości: O uwydatnianiu pozytywnych wspomnień z pamięci autobiograficznej. *Czasopismo Psychologiczne*, *25*(1), 159-164. https://doi.org/10.14691/CPPJ.25.2.159