MASTERARBEIT | MASTER'S THESIS

Titel | Title

The Relationship of Executive Functions and Multilingualism in Dyslexic Adults on the Functional and Behavioral Level

verfasst von | submitted by

Rixa Käthe Gruhnert BSc

angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien | Vienna, 2025

Studienkennzahl lt. Studienblatt | Degree programme code as it appears on the student record sheet:	UA 066 840
Studienrichtung lt. Studienblatt | Degree programme as it appears on the student record sheet:	Masterstudium Psychologie
Betreut von | Supervisor:	Assoz. Prof. Narly Golestani BSc PhD
Mitbetreut von | Co-Supervisor:	lic. Olga Kepinska MA MA PhD

Abstract

The present study aimed to examine whether multilingualism moderates behavioral and neural differences between adults with dyslexia (n = 29) and non-dyslexic controls (n = 29). matched on age, sex, and spoken multilingual proficiency. The sample consisted of well-educated francophone young adults who were highly multilingual. Behavioral outcomes included inhibition, measured by the executive control component of the ANT-I, and verbal working memory, assessed with the backward digit span test. Neural outcomes involved ROI-to-ROI based resting-state fMRI connectivity within predefined inhibition and working memory networks. Behavioral analyses utilized multiple linear regression for working memory and generalized linear regression for inhibition. Dyslexics showed worse inhibitory performance compared to their non-dyslexic peers ($t(47.04) = -3.01$, $p = 0.004$), while no difference in verbal working memory performance was found. Multilingual proficiency showed no significant effect on either verbal working memory or inhibition and did not appear to moderate the relationship between dyslexia and behavioral or connectivity measures. Resting-state analysis using the CONN toolbox identified visual differences in connectivity patterns for both inhibition and working memory networks; however, these differences did not survive FDR correction. The findings contribute to understanding the neural correlates of dyslexia and suggest limited modulatory influence of multilingualism on behavioral and neural profiles. Implications for future research directions are discussed.

Abstract

Die vorliegende Studie untersuchte Moderationseffekte von Mehrsprachigkeit auf Unterschiede zwischen Erwachsenen mit Lese-Rechtschreibschwäche (n = 29) und nicht-legasthenen Kontrollpersonen (n = 29) sowohl auf der Verhaltensebene als auch auf der neuronalen Konnektivitätsebene. Die Kontrollpersonen waren hinsichtlich Alter, Geschlecht und gesprochener Mehrsprachigkeit den Legasthenikern möglichst ähnlich. Die Stichprobe bestand aus gebildeten, größtenteils mehrsprachigen frankophonen jungen Erwachsenen. Verhaltensmessungen umfassten Inhibition, gemessen anhand der exekutiven Kontrollkomponente des ANT-I, und das verbale Arbeitsgedächtnis, gemessen mit dem Backward Digit Span Test. Die neuronalen Merkmale umfassten die ROI-zu-ROI-basierte fMRT-Konnektivität im Ruhezustand innerhalb vordefinierter Inhibitions – und Arbeitsgedächtnisnetzwerke. Die Verhaltensanalysen verwendeten multiple lineare Regression für das Arbeitsgedächtnis und generalisierte lineare Regression für die Inhibition als abhängige Variablen. Legastheniker zeigten im Vergleich zu ihren nicht legasthenen Altersgenossen eine schlechtere Inhibitionsleistung ($t(47.04) = -3.01$, $p = 0.004$), während kein Unterschied in der Leistung des verbalen Arbeitsgedächtnisses festgestellt wurde. Mehrsprachigkeit hatte keinen signifikanten Einfluss auf das verbale Arbeitsgedächtnis oder die Inhibition und schien die Beziehung zwischen Legasthenie und Verhaltens- oder Konnektivitätsmaßen nicht zu moderieren. Die Ruhezustandsanalyse mit der CONN-Toolbox identifizierte visuelle Unterschiede in den Konnektivitätsmustern sowohl für das Inhibitions- als auch für das Arbeitsgedächtnisnetzwerk; diese Unterschiede hielten jedoch einer FDR-Korrektur nicht stand. Die Ergebnisse tragen zum Verständnis der neuronalen Korrelate von Legasthenie bei und deuten auf einen begrenzten modulatorischen Einfluss der Mehrsprachigkeit auf Verhaltens- und neuronale Profile hin. Implikationen für zukünftige Forschungsrichtungen werden diskutiert.

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The Relationship of executive functions and multilingualism in dyslexic adults on the functional and behavioral level.

Dyslexia, a neurodevelopmental disorder primarily affecting reading abilities, is increasingly understood to involve broader cognitive challenges beyond phonological processing, notably in executive functions such as inhibition and verbal working memory. While research on both dyslexia and multilingualism in relation to executive functioning has been a topic of interest for decades, both lines of research have been mostly conducted separately from each other. Further, while childhood dyslexia is quite well-explored, few studies explicitly examine the combined impact of dyslexia and multilingualism on executive functioning at both behavioral and neural levels in adults. Most findings report task-based activation differences in reading-related networks, while assessments of resting-state network connectivity remain underexplored, specifically related to executive functioning networks. This study bridges the existing gap in the literature by investigating how multilingualism influences both the behavioral expression and resting-state functional connectivity of inhibition and verbal working memory networks in adult dyslexics. It aims at offering novel insights into compensatory mechanisms and cognitive reserve that may reshape our understanding of dyslexia in an increasingly multilingual world.

Dyslexia

Dyslexia is a neurobiological disorder characterized by difficulties in various language-related skills despite adequate intelligence, schooling, and willingness to learn (Schurz et al., 2015). Core deficits include diminished phonological awareness, word reading accuracy, reading fluency and slower writing rates, which are reflected in slow and effortful reading, difficulties decoding syllable-rich words, and heightened spelling error rates. The phonological core deficit hypothesis posits that these difficulties stem from impaired phonological processing, particularly in mapping speech sounds to written symbols, which is widely regarded as a central mechanism in dyslexia (Stanovich, 1988; Vellutino et al., 2004). However, research increasingly highlights broader cognitive deficits beyond phonology and implying interactions between genetic and environmental factors (Doust et al., 2022; Theodoridou et al., 2021).

For instance, a longitudinal study revealed persistent verbal working memory but not visuospatial cognitive function impairments (John et al., 2022). Smith-Spark and colleagues (2017) could not disentangle issues with executive control from phonological processing deficits as an alternative underlying mechanism of fluency deficits in dyslexic adults. Short-term memory deficits for item order were found in adults with dyslexia (Hachmann et al., 2014; Trecy et al.,

2013), as well as processing speed impairments (Callens et al., 2012). These findings align with evidence of auditory temporal processing, executive function, and orthographic learning challenges related to dyslexia (Facoetti et al., 2000; Nergård-Nilssen & Hulme, 2014).

Dyslexia – functional imaging differences

While behavioral differences between dyslexics and non-dyslexics are quite well-known, emerging research highlights differing brain activation and connectivity patterns connected to adult dyslexia. A comprehensive whole-brain analysis assessed task-based connectivity in children and young adults (Finn et al., 2014), applying a data-driven node selection. During word and nonword rhyming tasks, all age groups displayed decreased lateralization of language to the left hemisphere, increased connectivity to limbic and default mode networks, and persisting connectivity to a left-hemispheric anterior language region, among others. Turker and colleagues (2023) proposed that task-related connectivity patterns may pose a neural marker for dyslexia, which may directly relate to behavioral performance. Their findings of altered network dynamics indicate broader compensatory attempts across distributed regions, particularly involving right-hemispheric areas like the right ventral occipito-temporal cortex and the cerebellum. However, whether this task-related altered network connectivity persists at rest remains unclear.

Relating to resting-state networks, impaired readers frequently show reduced connectivity between the inferior frontal gyrus (IFG), a region implied in inhibition (Schaum et al., 2021) and temporo-parietal regions (Cheema et al., 2021; Finn et al., 2014; Schurz et al., 2015). Further, domain-general networks were found to be less well connected with reading-related regions at rest in impaired readers, with this group showing a negative correlation between reading accuracy and connectivity between the left IFG and the supramarginal gyrus (SMG), fusiform gyrus, and inferior temporal gyrus. However, while domain-general resting-state networks such as the default mode network, salience network, and dorsal attention network do show some connectivity to resting-state reading-related ROIs, their connectivity does not appear to be related to actual reading behavior (Cheema et al., 2021). Results from a resting-state EEG study support these findings: in the alpha band, dyslexics showed a more integrated network topology compared to typical readers, suggesting stronger but less specialized connectivity in dyslexic adults, which may indicate compensatory mechanisms or maturational differences (Fraga González et al., 2018). Due to the altered connectivity within reading networks at rest (Cheema et al., 2021), and findings of persistently weaker intrinsic fronto-parietal attention

network connectivity in dyslexics (Koyama et al., 2013), it seems plausible that for adult dyslexics, inhibition and working memory deficits may be reflected in altered functional connectivity within corresponding networks at rest.

In summary, dyslexia is a complex disorder most commonly identified in childhood, with core deficits persisting into adulthood where it may be masked by compensatory mechanisms (Moojen et al., 2020). In addition to impairments at the behavioral level, emerging studies show altered brain connectivity in dyslexic adults at rest, mainly in reading-related networks, which partly include regions related to executive functioning. These alterations likely contribute to difficulties with attention control, cognitive flexibility, and working memory – key components of executive functioning that are critical for fluent reading. These findings underscore the need to conceptualize dyslexia as a multiple-deficit disorder, where interactions between phonological weaknesses, executive function impairments (e.g., inhibition, working memory), and broader cognitive inefficiencies collectively contribute to its complexity (Fostick & Revah, 2018; Ozernov-Palchik et al., 2022). In line with this, various studies present impairments in executive functions in dyslexic individuals (Gooch et al., 2011; Horowitz-Kraus, 2014).

Executive Functions and Adult Dyslexia

In her review, Diamond (2013) outlines executive functions, also referred to as cognitive or executive control, as encompassing a set of higher-order mental processes essential for focusing and maintaining attention, particularly in situations where automatic responses or intuition may not suffice (Espy, 2018; Miller & Cohen, 2001). Although three fundamental executive functions are generally agreed upon: inhibition (which includes self-regulation and selective attention to manage interference), working memory, and cognitive flexibility (Lehto et al., 2003; Miyake et al., 2000), there remains some controversy regarding the definition and measurement of inhibition and working memory. Similarly, the underlying neural networks supporting executive functions are subject to variability and discussion. As this study will focus on verbal working memory and inhibition, both are described in more detail below.

Verbal Working Memory and Dyslexia

Verbal working memory - involving actively preserving and manipulating a limited quantity of verbal information for a behavioral purpose (Bacon et al., 2013; Baddeley, 2003; McLoughlin et al., 2008; Smith-Spark & Lewis, 2023; Swanson & Hsieh, 2009) - has been reported to be impaired in dyslexic individuals (Brosnan et al., 2002; Nergård-Nilssen & Hulme,

2014). More general working memory deficits having been proposed to be a hallmark characteristic of adult dyslexia (Bacon et al., 2013; McLoughlin et al., 2008; Swanson & Hsieh, 2009), which extend into dyslexics' day to day lives in form of issues with short – and long-term memory, impacting confidence and leading to self-doubt (Smith-Spark & Lewis, 2023). Brosnan and colleagues (2002) found consistent decreased performance of dyslexic children and adults on the digit span procedure assessing verbal working memory. In a small sample of Norwegian dyslexic adults, Nergård-Nilssen and Hulme (2014) found that next to weaknesses in phoneme awareness and difficulties with rapid automatized naming, deficiencies in verbal working memory, assessed via auditory word presentation and backwards recall, were strongly related to spelling abilities in dyslexic adults. Here, dyslexic adults performed significantly worse on the verbal working memory task than their non-dyslexic peers. As such, the first hypothesis of the present work expects to replicate these findings:

H1: Dyslexic adults will perform worse on the backwards digit span task, assessing verbal working memory, than their matched non-dyslexic peers.

Inhibition and Dyslexia

Inhibition refers to the capacity to suppress automatic, habitual, or dominant responses to stimuli in favor of responses that are more relevant to the context and appropriate for the task at hand and may occur behaviorally in the form of response control, or cognitively, in the form of resisting distractor interference. Cognitive inhibition allows focusing on an appropriate target rather than distractors, thereby enabling choices in the decisions we make (Diamond, 2013). Previous findings support the role inhibition has in reading related processes as well as academic success (Brosnan et al., 2002; Doust et al., 2022; Doyle et al., 2018; Dvorak, 2024; Privitera et al., 2022; Trinczer et al., 2024). It is therefore not surprising that dyslexia has been linked to impaired inhibition performance in children. In children, worse inhibition performance has been frequently linked to dyslexia (Daucourt et al., 2018; Lonergan et al., 2019; Miyake et al., 2000; Reiter et al., 2005; Van Reybroeck & De Rom, 2020; Wang et al., 2012). The likelihood of dyslexia as well as inferior reading ability was specifically predicted by lower inhibition and updating performance, suggesting that both play an essential role in developmental dyslexia (Doyle et al., 2018). In their review, Butterfuss and Kendeou (2018) found that cognitive abilities such as inhibition, updating and shifting supported reading comprehension. Contrary to these

findings, Georgiou and Das (2018) found only task-switching to significantly predict reading comprehension in university students, while inhibition and working memory did not.

Regarding adults, the existing body of literature is much smaller when it comes to dyslexia and inhibition deficits. Brosnan and colleagues (2002) found that difficulties with inhibiting distractors as well as the sequencing of events persist into adulthood, a finding extended to inhibitory mechanisms on the Stroop task for adults with dyslexia (Proulx & Elmasry, 2015). One notable study by Smith-spark and colleagues (2016) found that adults with dyslexia performed less accurately on a go/no-go task when it came to inhibiting non-habituated stimuli. One of two stimuli were presented, each requiring a different response in the form of two keyboard keys. After building habituation for 40 trials, the non-habituated stimulus was presented in 20% of the following trials, necessitating participants to depart from their customary response. While there was no significant difference between dyslexics and non-dyslexics with regards to their reaction times (to both habituated and non-habituated stimuli), dyslexics showed significantly worse accuracy in responding to the non-habituated stimulus. Given these findings, I expect to replicate the following relationship between dyslexia and cognitive inhibition:

H2: Dyslexic adults will perform worse on a measure of inhibition, than their matched non-dyslexic peers.

Multilingualism, Executive Functioning, and Dyslexia

Multilingualism refers to the ability of an individual, community, or society to communicate effectively in more than one or two languages, involving speaking, reading, writing, and understanding multiple languages. While most research has treated bilingualism as a dichotomous category, recent works have called for a more continuous approach, treating multilingualism as a spectrum of experiences (DeLuca et al., 2019; Kepinska et al., 2023). Executive functions and reading abilities have been frequently related to one another, in first as well as non-native languages (Relyea et al., 2023; Swanson et al., 2017), with the relationship likely being bi-directional (Schmitt et al., 2017). In healthy populations, bilingual advantages in executive functioning are frequently reported for both older and younger individuals (Antoniou, 2019; Bialystok, 2015) and are a topic of much controversy (for a review contesting the bilingual advantage, see Paap and Greenberg, 2013). As Dentella and colleagues (2024) summarize, the most consistently reported benefits of bilingualism relate to executive functioning, while disadvantages may be found in the verbal domain (Bialystok et al., 2008; Luo et al., 2013;

Pelham & Abrams, 2014). Bilinguals outperform monolinguals on tasks described as requiring working memory (for a review, see Grundy, 2020; Hervais-Adelman et al., 2011; Monnier et al., 2022), executive control (Hervais-Adelman et al., 2011), task-switching (Prior & MacWhinney, 2010; Stasenko et al., 2017) and inhibition (Grundy & Timmer, 2017). In addition to task demands, task characteristics, age of acquisition (AOA) of the second language, second-language abilities (Berkes & Bialystok, 2022), educational background (Gollan et al., 2011), as well as linguistic distance (Xia, 2021) and script differences between them (Yang et al., 2019) likely all influence found effect sizes for bilingualism's impact on executive functions (Achaa-Amankwaa et al., 2023; Alrwaita et al., 2024; Bialystok, 2015; Comishen & Bialystok, 2021).

A meta-analysis applying Bayesian statistics by Grundy (2020) highlights that the effects of bilingualism on executive functions, such as working memory and inhibition, are likely small but reliable. Comishen and Bialystok (2021) found that young bilingual adults performed better than their monolingual peers on an n-back task when conditions were more difficult, a finding reflected in their event-related potential analysis which suggested that bilinguals had higher working memory capacity and greater attentional resources. These findings indicate that long-term handling of multiple languages which may compete with one another is linked to increased working memory resources. Regarding bilingualism and inhibition, Green (1998) proposed that bilinguals inhibit non-target languages during speech production, which has since been supported by neural underpinnings of language-related interference control (Rodriguez-Fornells et al., 2005), with domain-general inhibition being reportedly applied to switching between languages (de Bruin et al., 2014). Other studies find no support of the adaptive control hypothesis, reporting no effects of intensity of dual-language use on inhibition tasks (Kałamała et al., 2020).

Beneficial effects of bilingualism are especially likely to be observed in populations which do not show peak cognitive performance, such as aging populations (Kousaie et al., 2014; Stevens et al., 2023), as ceiling effects may not take hold (Dentella et al., 2024; Grundy & Timmer, 2017). Findings by Romero and Uddin (2021) support this theory: While they review implications of the bilingual advantage for autistic children, they suggest the advantage may be especially relevant for populations in which executive function is compromised, such as in dyslexics. While some recent studies examined the effects of bilingualism in dyslexic children, research assessing the effects of multilingualism in adult dyslexics remains scarce. In dyslexic children, bilingualism has been related to better reading performance (de Azevedo et al., 2023) and better implicit learning in an artificial grammar learning task even comparable to non-

dyslexic controls (Vender et al., 2019), but no relationship was found between bilingualism and phonological awareness when known languages were phonologically different (Melloni, 2021). Other studies report detrimental effects for bilingual dyslexic children on executive function tasks tapping inhibition and working memory, attributed to increased cognitive load from managing two languages alongside reading (Jalali-Moghadam & Kormi-Nouri, 2015).

Thus, it remains unclear whether adult multilingual dyslexics may benefit from long-term management of more than one language to a larger extent than their monolingual peers, leveraging potential training effects of suppressing or inhibiting non-relevant languages as well as increased working memory resources to compensate observed deficits in inhibition and working memory (de Bruin et al., 2014; Grundy, 2020; Grundy & Timmer, 2017). On the other hand, during early adulthood performance is likely to be at its peak, leaving fewer possibilities for further improvement of cognition through environmental factors such as bi- or multilingualism (Bialystok et al., 2012; Struys et al., 2018). Nevertheless, the impact of bi- or multilingualism in dyslexic adults on executive functions such as inhibition and working memory remains under-explored. There is reason to believe that multilingualism may modulate the relationship between dyslexia and the executive functions verbal working memory and inhibition, with especially dyslexics potentially benefitting from additional language usage to bolster their inhibition and working memory skills: More multilingual participants may thus obtain better scores on the backwards digit span and ANT-I executive control measure than their less linguistically inclined peers. This relationship may be stronger for dyslexics than non-dyslexics:

H3a: Multilingualism moderates the relationship between dyslexia and verbal working memory on the behavioral level.

H3b: Multilingualism moderates the relationship between dyslexia and inhibition on the behavioral level.

Functional underpinnings of inhibition, working memory and multilingualism

Differences in inhibition and working memory performance on the behavioral level are found to be reflected in brain activation and connectivity patterns. This section reviews the current understanding of brain functional activation patterns and connectivity related to inhibition, verbal working memory, and multilingualism, with a particular focus on their neural underpinnings in both typical and dyslexic populations. First, evidence from task-based fMRI studies highlighting key cortical and subcortical regions engaged during inhibition and working

memory tasks is illustrated, emphasizing altered activation and connectivity patterns observed in dyslexia. Subsequently, resting-state functional connectivity findings that may reflect intrinsic network alterations associated with these executive functions are described. Finally, we consider how multilingual experience modulates these neural networks, potentially offering compensatory mechanisms that influence executive functioning and reading outcomes. Together, these insights provide a neurofunctional framework for interpreting the interplay between executive control, memory systems, and language experience in dyslexia.

Verbal Working Memory and Dyslexia – Functional Underpinnings

In healthy adults, meta-analytic findings indicate that verbal working memory is reflected in a reliable activation network comprising fronto-parietal and right-lateralized cerebellar areas, as well as basal ganglia nodes. Hemispheric specialization patterns featured bilateral frontal involvement in addition to left-parietal and right-cerebellar asymmetries, suggesting a need to revise established left-hemisphere frameworks for verbal working memory organization (Emch et al., 2019). The fronto-parietal network described by Emch and colleagues (2019) comprised left superior frontal gyrus (SFG), medial frontal gyrus, right middle frontal gyrus (MFG) and right IFG, the orbital and opercular parts of the left IFG, bilateral precentral gyri, bilateral supplementary motor areas (SMA) and left rolandic operculum. Lobule VI and crus I showed especially high activation within the cerebellum, and age was related to reduced activation in several regions of interest within a fronto-parietal network including additional temporal and insular involvement. Further, emerging evidence indicates a mediating role of the cerebellum specifically in verbal working memory related tasks (Timmann & Daum, 2007).

The findings of impaired working memory capabilities in dyslexic adults are reflected in differential brain activation during linguistic and non-linguistic auditory working memory tasks, with dyslexics showing greater activity in primary auditory, posterior superior temporal, and inferior parietal cortices compared to non-impaired readers (Conway et al., 2008). The cerebellum has been reported to show reduced activation as well as disrupted overall connectivity during reading-related tasks in dyslexic adults compared to non-dyslexic adults (Turker et al., 2023). Wolf and colleagues (2010), in a task-based fMRI study assessing network differences between dyslexic adults and non-dyslexic peers, outline two networks with altered connectivity patterns in dyslexic adults. Firstly, increased functional connectivity was found in left prefrontal and inferior parietal regions, which they describe as a phonological left-lateralized prefrontal

network. Second, altered connectivity patterns were found within a bilateral frontoparietal network, labeled as “executive network”, where dyslexics showed decreased connectivity between bilateral dorsolateral prefrontal and posterior parietal regions. Increased connectivity, associated with working memory task accuracy, was found for dyslexics in the left angular gyrus (AG), left hippocampal cortex and right thalamus. Vasic and colleagues (2008), in comparison, reported increasing working memory demand to be related to higher activation in left SFG, as well as the left and right IFG. Less activation compared to non-impaired readers was found in the MFG and in the superior parietal cortex. Dyslexics showed a correlation between verbal working memory performance (as measured by the backwards digit span task) and activation of prefrontal regions, while non-dyslexics did not. Schurz and colleagues (2015) further found evidence in favor of task-related connectivity alterations carrying over into connectivity at rest, albeit in the context of reading tasks.

Considering the role impaired working memory appears to play in adult dyslexia as well as the reports of dyslexia-related altered activation patterns in working memory related regions, it appears plausible that these alterations may be reflected in connectivity patterns at rest, similarly to reports of task-based reading-related connectivity patterns being replicated at rest (Schurz et al., 2015). Therefore, the fourth hypothesis targets resting-state connectivity differences between non-dyslexics and dyslexics within a network comprising working memory related regions:

H4: Dyslexics, in comparison to their matched peers, show altered connectivity patterns in a network comprising brain regions related to (verbal) working memory.

Inhibition and Dyslexia – functional Underpinnings

Many different networks and specific regions of interest have been proposed to underly executive functions such as inhibitory processes (Fan et al., 2005; Laird et al., 2011; Menon & D’Esposito, 2022). In regular readers, meta-analytic findings imply the dorsolateral prefrontal cortex (dlPFC), anterior cingulate cortex (ACC), superior and inferior parietal lobes, caudate, thalamus, putamen and cerebellar lobule VI and VII in inhibitory processes (Niendam et al., 2012). Cognitive control, on the other hand, was related to activation in the dlPFC, frontopolar and orbitofrontal cortex, ACC, and cerebellum, among others. The authors highlight connectivity between the prefrontal cortex (PFC) and cerebellum in inhibitory processes, as well as the supporting role of the ACC and related medial frontal regions in cognitive control processes. This is in line with findings linking the cerebellum to executive control (Brunamonti et al., 2014).

Specific brain areas reported to be related to inhibition in healthy adults are the ACC and IFG (Fan et al., 2005; Korucuoglu et al., 2021), MFG, right-lateralized fronto-parietal regions, SFG, bilateral anterior insula, frontal opercula, and anterior cingulate gyrus (ACG) (Korucuoglu et al., 2021; Laird et al., 2011).

While no study, to the best of my knowledge, specifically assesses resting-state connectivity related to inhibition in dyslexic adults, two meta-analytic findings highlight altered activation in regions related to inhibition in dyslexics compared to their non-dyslexic peers: Farah and colleagues (2021) assessed executive functioning deficits and their neural underpinnings in dyslexics across development and into adulthood. For adults aged 22 or older, both decreased and increased activation was reported across different studies for the left IFG, as well as decreased activation in the left thalamus and left parietal lobule, while bilateral superior occipital gyri showed increased activation. The frontal lobe has been proposed frequently as central to response inhibition, and impairments in its connectivity to the cerebellum have been found in dyslexics (Smith-Spark & Gordon, 2022). Findings by Schurz and colleagues (2015) found reduced fronto-temporal connectivity in dyslexic children and adults, relating to fusiform, inferior temporal, middle temporal and superior temporal gyrus as well as the left IFG, both during reading tasks and at rest. This implies a task-independent, more permanent disruption which is unrelated to performance differences across groups. It is thus not implausible that dyslexics performing worse on inhibition tasks may show altered connectivity in comparison their non-dyslexic peers in a network of regions implied in inhibitory processes.

In dyslexics, task-based activation as well as resting-state data relating to inhibitory processes is scarce. Most findings report task-based activation alterations in regions of interest to inhibitory processes, while the primary focus frequently rests on reading-related regions or networks. This study aims to bridge the gap in literature by assessing whether worse inhibitory performance in dyslexic adults is reflected in altered resting-state connectivity within a network of regions relevant to inhibitory processes. Based on the task-related activation studies in this field as well as one report of altered connectivity at rest, the fifth hypothesis targets resting-state connectivity alterations within an inhibition network for dyslexics compared to non-dyslexics:

H5: Brain areas related to inhibition tasks show altered connectivity patterns at rest for dyslexics compared to non-dyslexic controls.

Multilingualism

The functional studies discussed previously do not give information on participants' language backgrounds outside of the language used for assessment (Li et al., 2023; Schurz et al., 2015). However, resting-state functional connectivity has been proposed as a potential neural marker for first-and second-language reading abilities (Liu et al., 2016; Zhang et al., 2014), and second-language exposure and proficiency have been found to impact network connectivity within the three attention networks as assessed by the Attention Networks Test (Dash et al., 2022). Here, increasing second-language proficiency was related to weaker functional connectivity between the executive control network seed (left SFG) and visual areas, while there was stronger resting-state connectivity between right ACG and right precentral gyrus.

Hervais-Adelman and colleagues (2011) identified two key neural systems for executive language control in bilinguals: The Cortical Fronto-Parietal Network, comprising the left IFG (pars triangularis and opercularis), middle frontal, left precentral, and angular gyri as well as the left superior parietal lobule (SPL) and (pre-) SMA. The authors relate this network to cross-linguistic interference resolution, or in other words, the inhibition of inappropriate language output when speaking. The Fronto-Basal-Ganglia System, on the other hand, comprises left-hemispheric caudate, putamen, and globus pallidus, and is further connected to the prefrontal cortex via cortico-striatal loops. This network appears to play a role in automatic language selection, suppression of non-target languages and coordination of language-specific articulatory plans. Taken together, these networks may manage inhibitory control as well as language selection in bilingual adults. Finally, the cerebellum, in which disrupted functional connectivity was detected for dyslexic adults during reading tasks (Turker et al., 2023), has been identified to show altered functional activation in bilinguals: its left hemisphere was related to cognitive control functions in bilinguals, connecting with more prefrontal, parietal and subcortical brain areas, while its right hemisphere contributed to language control in bilingual language production tasks (Yuan et al., 2023).

Similar to the demands posed by musical training, language acquisition and management may offer multi-faceted remediation for dyslexic learners by engaging auditory processing and linguistic systems as well as higher-order cognitive networks such as executive function and memory systems (Schroeder et al., 2016). Bi- or multilingual experience may pose inhibition and working memory training through constant inhibition of non-target languages as well as increasing working memory capacity (Comishen & Bialystok, 2021). Non-linguistic memory

training in various forms was found to affect activation patterns within the fronto-parietal network (Vartanian et al., 2022), with increased activation of the left inferior parietal lobule, right MFG, and medial frontal gyrus bordering on the cingulate gyrus were found after training, while decreased activation as found in bilateral inferior parietal lobules, middle and SFG, and medial frontal gyrus bordering on the cingulate gyrus. The frontal lobes showed specific engagement during interference or top-down regulation. As such, increasing language experience may be reflected in similar network changes.

Bilingualism has been further linked to cognitive persistence (effortful task engagement) via engagement and modulation of the cingulo-opercular network, specifically increased IFG and decreased ACC engagement, which suggests more efficient conflict resolution during executive function tasks. This network's efficiency in early multilinguals may explain superior executive function performance (Dash et al., 2022; Teubner-Rhodes, 2020). It is thus plausible that multilingualism-related connectivity changes at rest may be found in dyslexic adults between regions of inhibition and working memory networks. To conclude, multilingualism-induced neural changes might counteract dyslexia-related functional anomalies in inhibition and working memory networks (Berkes & Bialystok, 2022; Teubner-Rhodes, 2020).

H6: Multilingual experience modulates dyslexia-related connectivity alterations in inhibition and working memory networks at rest. Specifically, multilingual experience will be especially impactful for dyslexics in comparison to non-dyslexics at rest.

Aims & Approach

The present study aims to further assess the relation between executive functions – more specifically verbal working memory and inhibition – and adult dyslexia, both at the functional as well as the behavioral level while taking multilingual backgrounds into account. Specifically of interest will be (a) whether verbal working memory and inhibition deficits on the behavioral level will be found for dyslexic adults; (b) whether multilingual experience may modulate the relationship, specifically whether multilingual experience may prove beneficial for dyslexic readers regarding inhibition and working memory; (c) whether behavioral differences may be reflected in altered connectivity within inhibition and working memory networks; and (d) whether multilingualism forms a potential modulator in the relationship between dyslexia and intrinsic inhibition as well as working memory network connectivity.

Here, a two-step approach will be followed. Initially, predictive power of multilingualism and dyslexia diagnosis, as well as their interaction, will be assessed for behavioral inhibition and

working memory scores in a subset of participants matched in age, education and multilingualism, consisting of general speakers only. An exploratory analysis within the whole unmatched sample, including dyslexics (general speakers) and non-dyslexics (general speakers, polyglots, hyperpolyglots) will be conducted. Next, differences in connectivity patterns at rest will be assessed for both groups, as well as the impact which multilingualism may have on both inhibition and verbal working memory networks for both dyslexic and non-dyslexic participants.

While task-based fMRI identifies activation patterns during specific EF demands, resting-state connectivity captures intrinsic network organization that may underly trait-like cognitive capacities. By deriving networks from meta-analyses of inhibition and working memory tasks, this study tests whether task-related EF deficits in dyslexia are reflected in stable, resting-state network architecture.

Materials, Methods and Procedure

The present study was able to process the data acquired within the WPAptitude project, which aimed at assessing factors underlying language aptitude and included extensive testing of various cognitive and linguistic abilities, musicality, and perceptuo-motor skills. For the present work, especially inhibition and verbal working memory will be relevant, while other domains will not be described. For interested readers, the original study is described in more detail in the work by Rampinini and colleagues (2024).

Participants

The complete sample included 151 healthy, adult French-speaking individuals, out of which 67.11% were female (N = 102), with an overall mean age of 24.5 years (18 – 47 years) and a mean education of 16 years (11 – 26 years). Languages spoken ranged from one to 27 (M = 5.48, SD = 3.80), with six participants being identified as hyperpolyglots, 133 as general speakers and twelve as polyglots, according to the definition of Jouravlev and colleagues (2021). One participant was excluded due to missing values on variables of interest. Participants were included if their proficiency in French was advanced even when it was not their native language. Individuals with dyslexia were included if they had an official diagnosis (N = 29), while simultaneous interpreters as well as professional musicians were excluded. Participants were recruited through flyers and online advertisements from Geneva, neighboring Swiss cantons and close regions of France. All participants gave informed consent for all experimental procedures as well as data re-use within the open science framework, and the study was ethically approved by the Geneva Cantonal Ethical Commission (CCER).

Data was gathered online as well as in-person throughout multiple sessions by six data collectors of either native or advanced French level. Within Session 1, unsupervised online data collection was performed, while Session 2 included supervised online behavioral data collection, performed using the Gorilla web interface (Anwyl-Irvine et al., 2020). Session 3 included additional behavioral testing in person, at the Human Neuroscience Platform of "Campus Biotech" in Geneva in a testing room where a laptop, mouse and headphones with a microphone were provided. Finally, Session 4 included the collection of neuroimaging data. Documentation, instructions, and interactions happened in French, all questionnaires and tasks were presented in French or adapted for use in French, which was verified by at least one native speaker. Behavioral task instructions and audio stimuli were read out by a commercial voice generator to avoid variance in inflection (female; https://www.naturalreaders.com/commercial.html; Voice "Renee France", speed = -1).

Within the present study, nearest-neighbor propensity score matching was performed to generate a non-dyslexic control group equal to dyslexic participants in age, sex and multilingual experience (as assessed by entropy speaking scores; see description below). The distribution of propensity scores as well as balance statistics may be seen in Appendix A. Within the subsample, dyslexics' mean age was 22.9 years (18.1 - 35.2 years) while the non-dyslexics' mean age was 23.52 years (19.5 - 29.2 years). Both groups were comprised of only general speakers, with the number of known languages ranging from one to eight for non-dyslexics (M = 4), and one to six for dyslexics (M = 3.72). Both groups were quite well-educated: While dyslexics showed a mean of 15.7 years of education ranging from eleven to 21 years, regular readers showed a mean education of 15.8 years, ranging from 13 to 19 years. As in the complete sample, both subgroups included slightly more women than men. The dyslexic group included eleven men (37.9%), while the matched control group included ten (34.5%).

Tasks

Verbal Working Memory

The digit span task (Wechsler, 2008) was applied to measure verbal working memory, specifically the backwards component. Verbally presented digits must be retained in memory as well as transformed or manipulated to reverse their order, which makes this task frequently applied as a verbal working memory task (St Clair-Thompson & Allen, 2013; Willcutt et al., 2005). During this task, participants listened to increasingly longer sequences of digits, which

they then needed to recall in backwards order, giving responses via the upper numeric keypad. Response modality for this task has been found to lead to similar performance (Ryan et al., 2014). The task was administered through headphones. Scoring followed the established procedure: The longest sequence accurately recalled forms the score, e.g., a sequence of 5 digits recalled correctly, followed by a mistake in the following 6-digit sequence recall, led to a score of 5. Participants recalled on average 4.98 digits in the correct order (*SD* = 1.32, *Min* = 2, *Max* = 8).

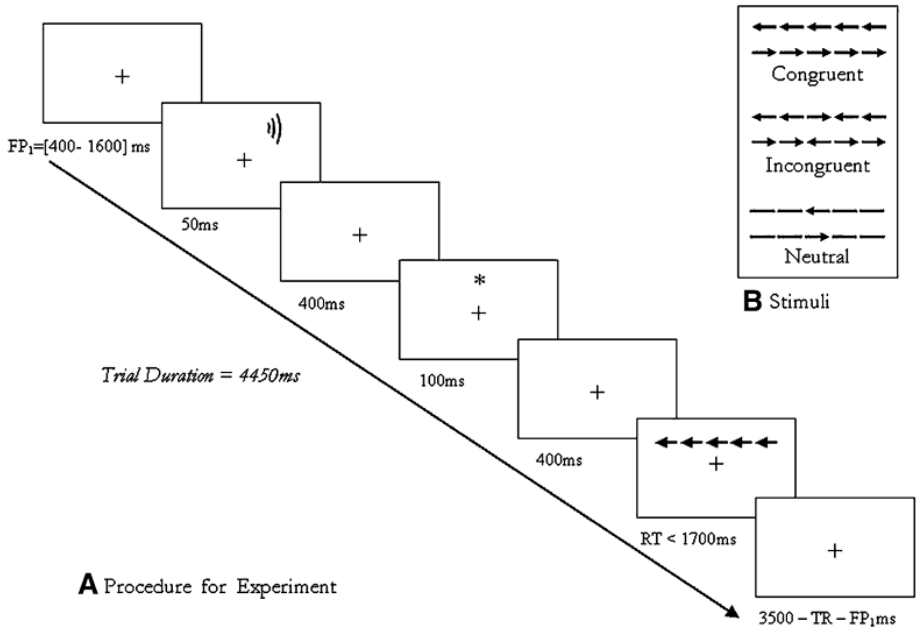
Inhibition

Inhibition was assessed by the executive control component of the Attention Networks Interaction task - ANT-I (Callejas et al., 2005). The ANT-I forms a classic approach to assess attention networks (executive control, alerting, orienting), and requires participants to detect the direction of an arrow while flankers, alerting sound cues, and orienting visual cues are presented. For the sake of brevity, only the procedure relating to executive control will be described in more detail, while an example sequence is outlined in Figure 1, A. Interested readers may consult the original works by Callejas and colleagues (2005) as well as Fan and colleagues (2005) for more information on the complete procedure.

Participants completed 432 trials with 18 possible conditions, leading to 24 trials per condition: The interactions between target direction and flanker direction (congruent, incongruent, neutral), as well as the position and presence of cues (visual: absent, above, or below the fixation cross; auditory: present or absent). Twenty practice trials were performed with feedback included, while three blocks of 144 trials were performed without feedback. For each trial, a fixation cross was constantly present at the center of the display, with the initial fixation point lasting between 400 to 1600ms. Auditory alerting cues (2000Hz) were presented for 50ms in relevant trials, otherwise the 50ms were spent during silent fixation. This sequence was followed by another fixation period of 400ms, after which the orientation sequence lasted for 100ms (cue congruent with the target position, incongruent with the target position, or absent). The final sequence consisted of flankers being presented next to the target arrow (Figure 1, B), either pointing in the opposite direction (incongruent condition) or the same direction as the target (congruent condition). The neutral condition showed lines without arrowheads next to the target. Participants were asked to indicate the direction of the central target via response keys (“A” for arrows pointing to the left, and “L” for arrows pointing to the right, on the provided keyboard) as rapidly and accurately as possible.

Figure 1.

Example trial of the ANT-I task procedure.



Note. A. Procedure of the ANT-I task as seen in Callejas and colleagues (2005), including an alerting cue and congruent orienting cue (asterisk) as well as congruent flanker arrows bracketing the target. B. Two possibilities of congruent, incongruent and neutral conditions of the flanker stimuli.

Inhibition scores were calculated by subtracting the mean reaction times (in ms) of congruent flanker trials from incongruent flanker trials, as performed in the measurement of executive control performance in the ANT-I (Callejas et al., 2005). When resulting scores were small, inhibitory processes necessary within the incongruent condition appear to be less time-intensive and effortful, indicating better inhibitory performance. Trials with incorrect or missing responses were excluded, as well as trials showing extreme reaction times of less than 200ms or more than 1200ms. Inhibition scores (RT differences) ranged from 18.28ms to 159.95ms (M=65.55, SD=28.98). Reliability of the inhibition scores as assessed by the ANT-I executive control measure was reportedly high, with higher scores reflecting worse conflict resolution (Ishigami et al., 2016). Rampinini and colleagues, within the complete dataset out of which the subgroups were extracted for the present study, also report high reliability especially for the inhibition measure (2024).

Multilingualism

A measure of multilingualism was achieved via online, unsupervised self-ratings on the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian et al., 2007). The publicly available French adaptation was further extended to allow participants to give information on up to 50 languages regarding context of use, learning, history with the language, native-likeness and use choices. Further context information such as time spent within subcultures, online communities, social media, learning apps and everyday tasks was included to gain a more comprehensive overview of factors contributing to language learning, while the question relating to cultural identification was omitted. The questionnaire was completed for each language known or used by participants. While the LEAP-Q is a common questionnaire in multilingualism research, its recommended use relates to more qualitative descriptions of participants' language profiles (Marian et al., 2007). As the present work is based on a quantitative approach, a measure of participants' multilingual experience needed to be calculated (henceforth 'spoken multilingual proficiency index').

Following the approach used in previous works (Gullifer & Titone, 2020; Kepinska et al., 2023), variability in participants' spoken languages was calculated using Shannon's entropy equation (*H*; Shannon, 1948)(Benjamini & Hochberg, 1995) via the entropy R package (Hausser et al., 2012). This method accounts for the spoken proficiency across participants' languages.

$$H = -\sum_{i=0}^{n} p_i \ log_2 p_i$$

Within this equation, *n* indicates the total number of languages a participant speaks, and p_i indicates their proficiency relative to all languages' proficiency indices. Higher scores on this measure reflect more variability in a participant's language repertoire. Entropy increases with both the number of languages spoken and the evenness of proficiency distribution. Spoken multilingual proficiency index values range from 0 to log n, with one spoken language being reflected in a score of 0, while for two languages, maximum multilingual proficiency is at a value of 1. For six spoken languages, maximum multilingual proficiency is approximately 2.59, while for eight spoken languages, maximum multilingual proficiency index would be at 3.The matched non-dyslexic group reported four languages on average as forming part of their background, ranging from one to eight spoken languages (*SD* = 1.36), while the dyslexic group reported on average 3.72 spoken languages, ranging from one to six languages (*SD* = 1.51). Multilingual

proficiency index values ranged from zero to 1.6 for both non-dyslexic (M = 1.08, SD = 0.31) and dyslexic (M = 1, SD = 0.45) participants.

Other variables of interest

To perform a sanity check by assessing whether a dyslexia diagnosis would accurately reflect worse reading and spelling abilities, measures for both were included in the analysis. Text reading was assessed by participants' speed in correctly reading out loud two texts of increasing difficulty within three minutes, namely "Le Pollueur" and "L'Alouette" (Gola-Asmussen et al., 2010; Lefavrais, 1967), as fast and accurate as possible. The spelling measure formed part of the ECLA16+ test battery (Gola-Asmussen et al., 2010), wherein participants listened to words, pseudowords and irregular words, and being asked to write them down.

Analysis of Behavioral Data

All behavioral data analyses were performed within R (2021). Correction for multiple comparisons was performed applying False-Discovery-Rate correction (FDR) setting a significance threshold of $p < .05$ and a false discovery rate of 5% (Benjamini & Hochberg, 1995). This was applied to the correlation analysis as well as across regression results. In order to balance correction of false discovery rates with maintaining adequate power to detect effects of interest, covariates (age, sex, and education) were included as controls but were excluded from multiple comparison correction, as they did not form part of primary hypotheses (Benjamini & Hochberg, 1995; Gelman et al., 2012). False discovery rate correction was applied to the p-values of the primary predictors of interest (dyslexia, multilingualism, and their interaction) across the four regression models.

Functional Data

Resting-State Network selection

Neurosynth, a framework for automated synthesis of neuroimaging findings based on text-mining, allows the generation of large-scale meta-analyses for various psychological concepts and their associated brain activity changes (Yarkoni et al., 2011). The corresponding web interface (http:// neurosynth.org/) allows the extraction of activation coordinates related to key words, synthesized from literature which reports activation changes in relation to these terms of interest. Neurosynth's meta-analytic coordinate maps aggregate consistent activation patterns across diverse tasks and concepts, providing robust templates for defining inhibition and working

memory networks. This approach avoids circularity from task-specific activations while capturing domain-general EF circuitry. Inhibition and verbal working memory networks were thus acquired using the search terms “inhibition” and “working memory”, as “verbal working memory” was unavailable as a keyword.

Association test maps were extracted since they control for base rate differences between brain regions. Specifically, association test maps indicate more consistent activation in regions for studies which include the search term compared to studies which do not, allowing more confidence in extracted regions truly being involved in the process of interest. All provided maps are thresholded to correct for multiple comparisons at a false-discovery criterion of .01.

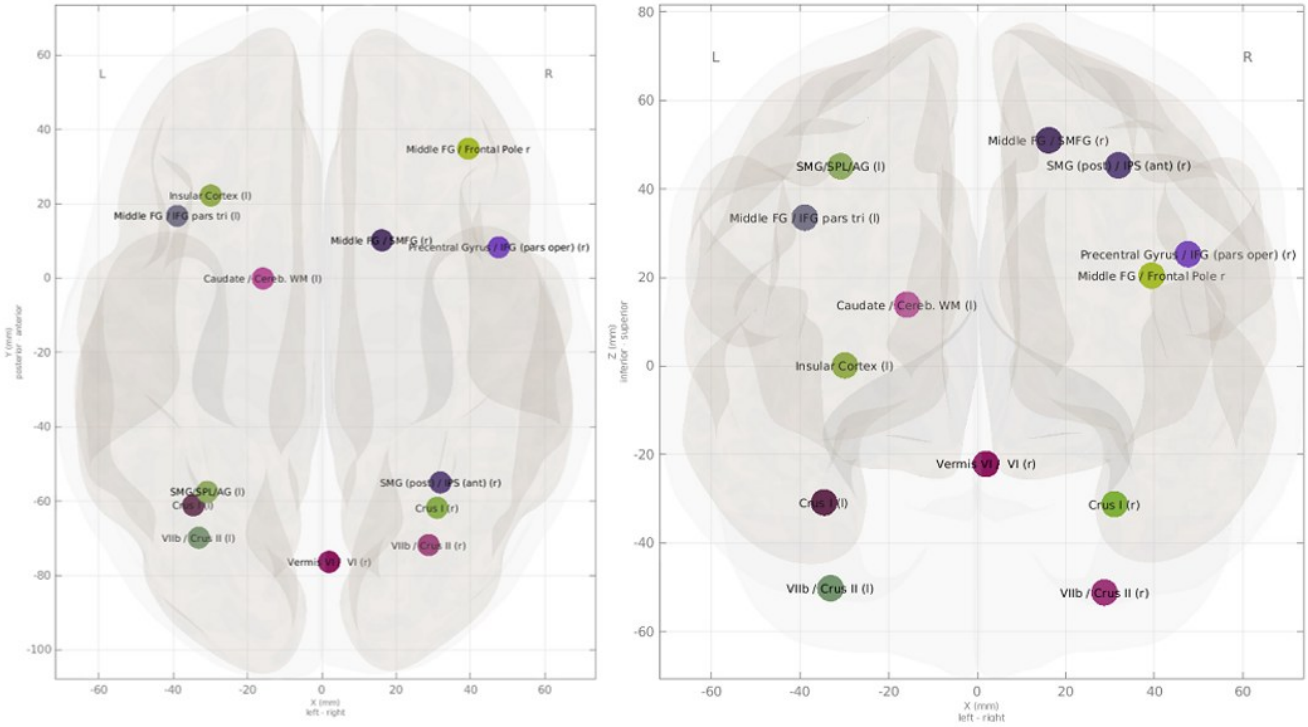
Statistical maps extracted from Neurosynth were further thresholded and clustered using the fsl-cluster tool from the FMRIB Software Library (FSL; Version 6.0.7.17; FMRIB Analysis Group, University of Oxford, 2021a). Clusters were defined at thresholds corresponding to $p < .001$, generating cluster indices and sizes used for subsequent ROI-to-ROI connectivity analyses using the CONN functional connectivity toolbox version 22a (Nieto-Castanon & Whitfield-Gabrieli, 2022). Only clusters equal to or exceeding a size of 20 voxels were included in further analyses. FSLeyes (FMRIB Analysis Group, University of Oxford, 2021b) was used to evaluate which brain regions according to the Harvard-Oxford Cortical and Subcortical Atlases as well as the Cerebellar Atlas in MNI52 space after normalization with FLIRT best matched the maximal activation of each cluster. For various clusters, more than one atlas region showed overlap with the maximal activation coordinates, see Appendix B for more detailed tables reporting exact percentages for each cluster.

The working memory mask yielded the following thirteen regions of interest across both hemispheres, listed according to cluster size (see Figure 2): Cluster 1: Left MFG extending into the IFG (triangular part); Cluster 2: Left posterior SMG extending into SPL and AG; Cluster 3: Right MFG extending into SFG; Cluster 4: Right posterior SMG; Cluster 5: Right MFG extending into the frontal pole; Cluster 6: Right crus I extending into right lobule VI; Cluster 7: Left precentral gyrus overlapping with the IFG, opercular part; Cluster 8: Left insular cortex; Cluster 9: Left Crus I; Cluster 10: Right Vermis VI extending into right lobule VI; Cluster 11: Left cerebral white matter extending into left caudate; Cluster 12: Right lobule VIIb extending into right Crus II and right VIIIa; Cluster 13: Left lobule VIIb extending into left Crus II. A table summarizing each Cluster’s involvement in working memory processes may be found in

Appendix C. To summarize, the network of regions of interest generated through Neurosynth appears to reflect working memory-relevant regions reasonably well.

Figure 2.

Regions of interest within the working memory network.

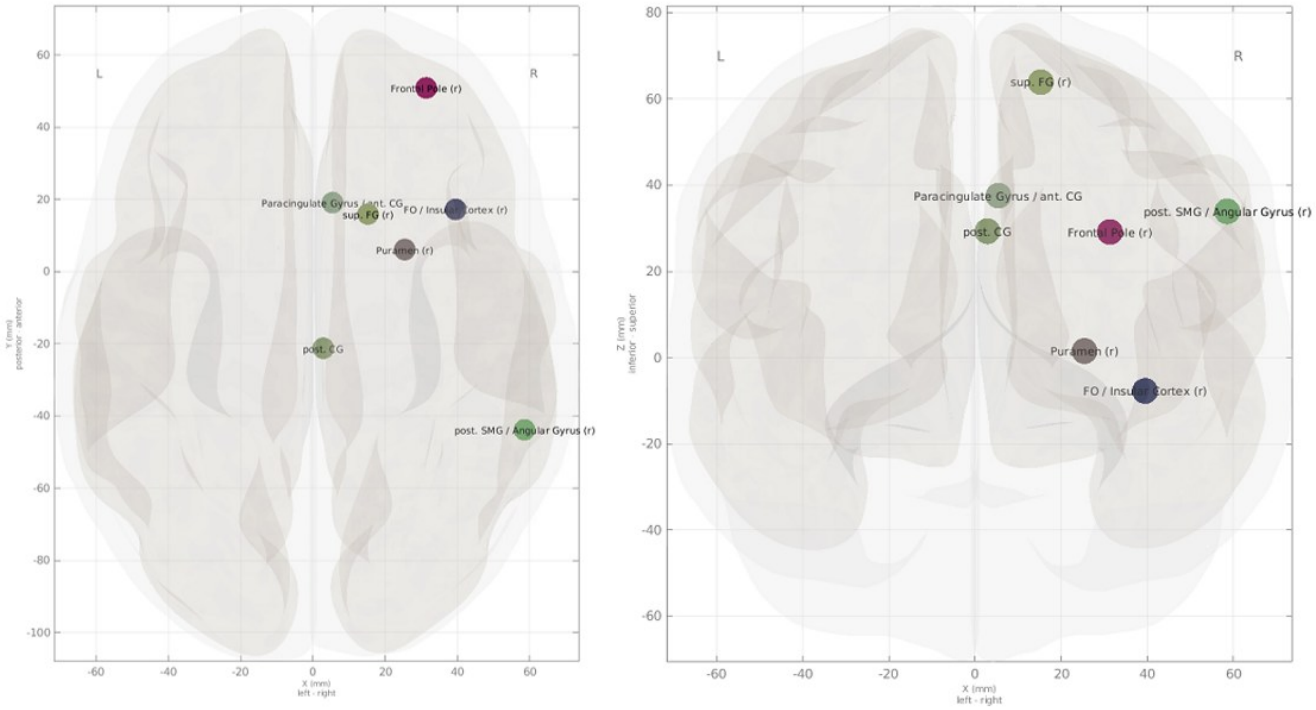


Note. Left: transverse/axial plane; Right: posterior view.

The inhibition mask yielded the following seven clusters overlapping with the following regions of interest, all of them within the right hemisphere (see Figure 3): Cluster 1: Frontal operculum cortex extending into insular and frontal orbital cortex; Cluster 2: Posterior SMG extending into AG; Cluster 3: Frontal pole; Cluster 4: Paracingulate gyrus extending into ACG; Cluster 5: Posterior cingulate gyrus; Cluster 6: SFG; and cluster 7: Right putamen. A table summarizing each Cluster's involvement in working memory processes may be found in Appendix C. To summarize, the acquired clusters appear to be involved in inhibitory processes, most prominently response inhibition.

Figure 3.

Regions of interest within the Inhibition network.



Note. Left: transverse/axial plane; Right: posterior view.

Image Acquisition and Preprocessing

Results included in this manuscript come from analyses performed using CONN (Whitfield-Gabrieli & Nieto-Castanon, 2012a; RRID:SCR_009550) release 22.a (Nieto-Castanon & Whitfield-Gabrieli, 2022) and SPM (Penny et al., 2011; RRID:SCR_007037) release 12.7771. **Preprocessing**: Functional and anatomical data were preprocessed using a flexible preprocessing pipeline (Nieto-Castanon, 2020a) including slice timing correction, outlier detection, and direct segmentation and MNI-space normalization. Temporal misalignment between different slices of the functional data (acquired in interleaved Siemens order) was corrected following SPM slice-timing correction (STC) procedure (Henson et al., 1999; Sladky et al., 2011). This correction uses temporal interpolation to resample each slice's BOLD time series to a common mid-acquisition time. Potential outlier scans were identified using Artifact Detection Tools (ART; Whitfield-Gabriele & Nieto-Castanon, 2012b) as acquisitions with framewise displacement above 0.9 mm or global BOLD signal changes above 5 standard deviations (Nieto-Castanon, 2022; Power et al., 2014), and a reference BOLD image was computed for each subject by averaging all scans excluding outliers. Last, functional and anatomical data were normalized into standard MNI

space, segmented into grey matter, white matter, and cerebrospinal fluid (CSF) tissue classes, and resampled to 2 mm isotropic voxels following a direct normalization procedure (Calhoun et al., 2017; Nieto-Castanon, 2022) using SPM unified segmentation and normalization algorithm (Ashburner, 2007; Ashburner & Friston, 2005) with the default IXI-549 tissue probability map template.

Denoising:

In addition, functional data were denoised using a standard pipeline (Nieto-Castanon, 2020b), which included the regression of potential confounding signals estimated using the CompCor method (Behzadi et al., 2007; Chai et al., 2012). Specifically, this involved the extraction of 5 noise components each from white matter and CSF timeseries, derived from principal component analysis (PCA) of BOLD signals within segmented masks, orthogonalized to the average BOLD signal, motion parameters, and outlier scans for each subject. The pipeline also regressed out motion parameters and their first-order derivatives (12 factors) (Friston et al., 1996), outlier scans (up to 56 factors) (Power et al., 2014), session effects and their first-order derivatives (2 factors), and linear trends (2 factors) within each functional run. Finally, bandpass frequency filtering was applied to the BOLD timeseries between 0.008 Hz and 0.09 Hz (Hallquist et al., 2013). From the number of noise terms included in this denoising strategy, the effective degrees of freedom of the BOLD signal after denoising were estimated to range from 71.5 to 89.9 (average 87.3) across all subjects (Nieto-Castanon, 2022).

Analysis of Functional Connectivity

Functional ROI-to-ROI connectivity matrices at the first level were estimated characterizing the functional connectivity between each pair of regions among seven ROIs. Functional connectivity strength was represented by Fisher-transformed bivariate correlation coefficients from a general linear model (weighted), estimated separately for each pair of ROIS, characterizing the association between their BOLD signal timeseries. In order to compensate for possible transient magnetization effects at the beginning of each run, individual scans were weighted by a step function convolved with an SPM canonical hemodynamic response function and rectified. The same was done for the thirteen ROIs comprising the working memory network.

Group-level analyses were performed using a General Linear Model (GLM, Nieto-Castanon, 2020d). For each individual connection a separate GLM was estimated, with first-level connectivity measures at this connection as dependent variables (one independent sample per

subject and one measurement per task or experimental condition, if applicable), and groups or other subject-level identifiers as independent variables. Connection-level hypotheses were evaluated using multivariate parametric statistics with random-effects across subjects and sample covariance estimation across multiple measurements. Inferences were performed at the level of individual connections (groups of similar connections). All results were thresholded at a corrected *p-FDR* < .05 connection-level threshold, while cluster-level thresholds were set to 'none', as mainly individual connections within each network were of interest. The first group-level analysis concerned non-zero resting-state functional connectivity at the connection level within dyslexic and non-dyslexic groups, for both inhibition and working memory networks. The second analysis performed was contrasting within-network connectivity between dyslexics and non-dyslexics for both inhibition and working memory networks. Finally, the correlation between network connectivity and the interaction term (dyslexia diagnosis X multilingualism) was calculated for each connection within CONN. For all analyses, age, level of education, and multilingual experience index were mean centered and included as covariates, while sex was estimated at the zero-level (male).

Results

Task-based Differences between Dyslexics and Non-dyslexics.

The following section describes the behavioral differences between dyslexics and non-dyslexics on both the inhibition as well as verbal working memory measures. Displayed in Table 1 are distributions and correlations between the independent variable Dyslexia, the potentially moderating variable Multilingualism (multilingual experience index), the dependent variables inhibition and verbal working memory (measured by the executive control component of the ANT-I task and backwards digit span test, respectively), as well as covariates (age, education and sex). Reading and spelling were further included to assess their impact on the dependent variables independent from dyslexia diagnosis. Whole-sample correlations (black) were corrected for multiple comparisons, while subgroup correlations within the dyslexic group (red) and non-dyslexic group (blue) were not. A correlation table listing exact uncorrected *p*-values as well as FDR-corrected *p*-values for whole-group correlations can be found in Appendix D.

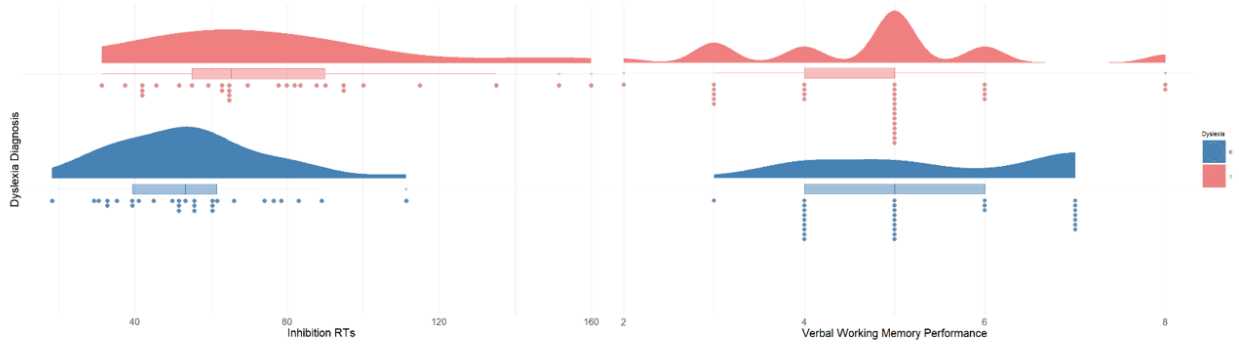
Reading and spelling were strongly correlated (r = .71, *pFDR* < .001), within subgroups this correlation appears to be stronger for dyslexics (r = .73, *p-uncorrected* < .05) than non-dyslexics (r = .45, *p-uncorrected*<.05). Unsurprisingly, age was significantly correlated with years of education (r = .36, *pFDR* = .02). Reading and spelling scores, as a continuous proxy

measure for dyslexia and sanity check, appear to differ between dyslexics and non-dyslexics in expected ways (see column 9, Table 1). Dyslexics had a mean reading score of 50.03 (*SD* = 4.20), while non-dyslexics scored at 53.11 (*SD* = 1.22) (*t*(32.68)= 3.79, *p* < .001). Spelling scores were also lower within the dyslexic group (*M* = 15.72, *SD* = 5.03) than within the non-dyslexic group (*M* = 21.03, *SD* = 4.02) (*t*(53.40) = 4.44, *p* < .001). Regarding the variables of interest, verbal working memory scores were significantly correlated with reading (r = .43, *pFDR* = .005) and spelling (r = .45, *pFDR* =.003), indicating that better reading and spelling abilities were related to better verbal working memory. Similarly, inhibition scores were significantly negatively correlated with spelling (r = -.45, *pFDR* = .003) and reading (r = -.36, *pFDR* = *.002*), indicating that better reading and spelling abilities were related to shorter RT scores and better inhibitory abilities. The relationship between verbal working memory and inhibition, while significant at the uncorrected level (*p-uncorrected* = .036), did not appear significant after multiple comparison correction (r = -.28, *pFDR* =.075). While multilingualism appeared to correlate with spelling abilities at the uncorrected level (r = .29, *p-uncorrected* = .027), multiple comparison correction rendered this relationship non-significant (*pFDR* = .070). The correlations between multilingualism and verbal working memory (r = -.12, *pFDR* = .496) as well as inhibition (r = -.22, *pFDR* = .161) was not significant.

In order to further assess the potential difference between the dyslexic and non-dyslexic groups regarding the verbal working memory and inhibition measures, as indicated by the variables' boxplots in the dyslexia columns in Table 1, two t-tests were performed and their results corrected for multiple comparison, leading to a significance threshold of *p* = .025. Figure 4 shows a visualization of distributions, as well as boxplots and exact data points for dyslexics and non-dyslexics on both dependent variables.

Figure 4.

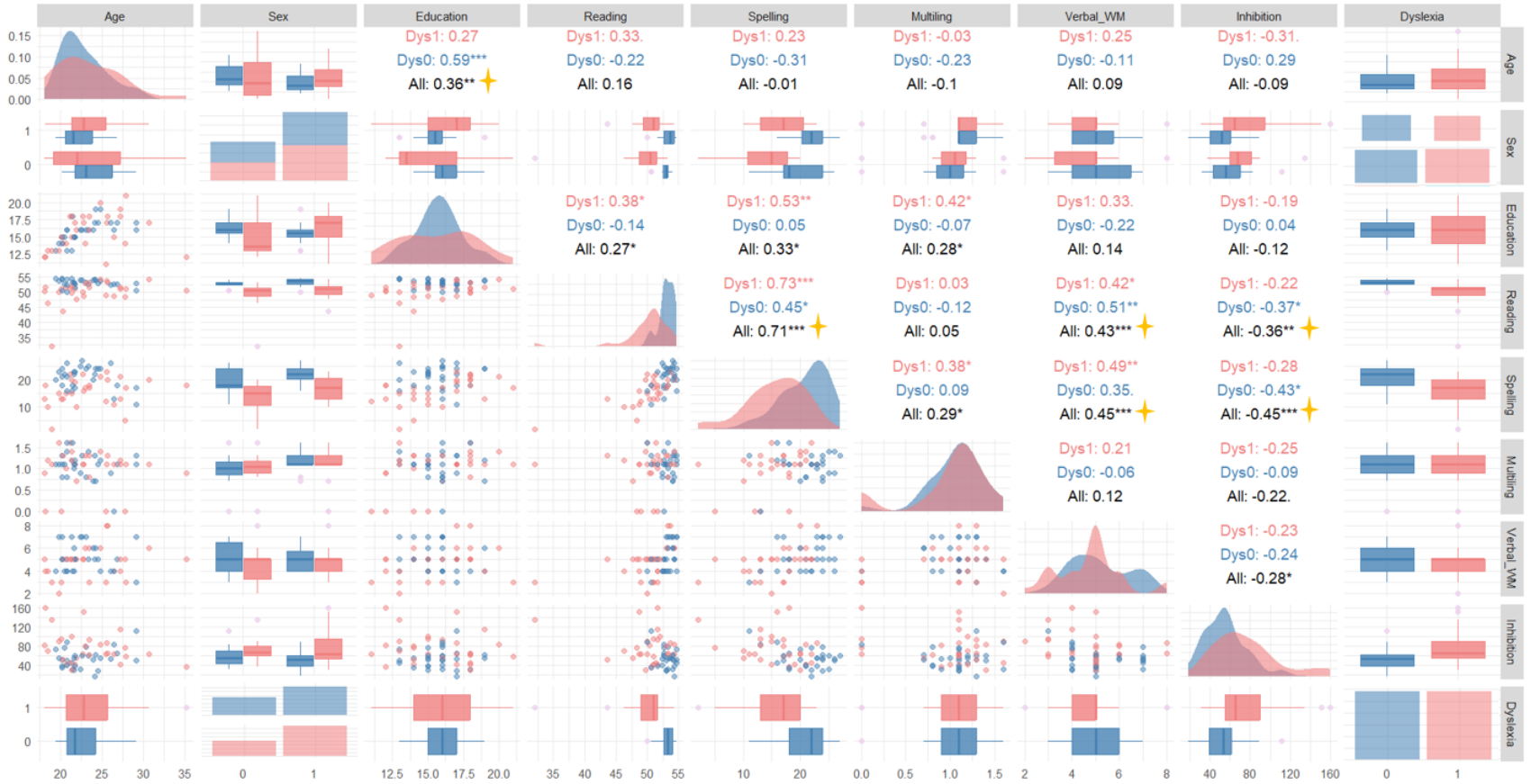
Raincloud plots for each subgroup and dependent variable.



Note. Distribution of inhibition scores in reaction times (RTs; left) and verbal working memory scores (right) for dyslexics (red; upper row) and non-dyslexics (blue; lower row).

Table 1.

Correlations and distributions for relevant variables, grouped by dyslexia diagnosis.



Note. N=58. While whole-group correlations were corrected for multiple comparisons, within-group correlations (dyslexic group: red, non-dyslexic group: blue) were not.♦.Correlation is significant at the .05 level (2-tailed) after p-FDR correction of whole-group multiple comparisons. ***. Correlation is significant at the 0.001 level (2-tailed), uncorrected. **. Correlation is significant at the 0.01 level (2-tailed), uncorrected. *. Correlation is significant at the 0.05 level (2-tailed), uncorrected.

Although dyslexics recalled on average fewer digits (M = 4.76, SD = 1.38) than their non-dyslexic peers (M = 5.21, SD = 1.24), this difference between groups was non-significant already at the uncorrected level (t(55.33) = 1.303, p = 0.198, 95% CI [-0.24, 1.14]). A significant difference was found for inhibition, where higher scores indicate lower performance. Dyslexics showed higher inhibition scores (M = 76.28, SD = 32.50) than their matched non-dyslexic controls (M = 54.81, SD = 20.36, t(47.04) = -3.01, p = 0.004, 95% CI [-35.79, -7.13]), indicating worse inhibition performance in milliseconds (ms) even when controlling for multiple testing. After threshold adjustment, this difference in means remained significant.

While these results support Hypothesis 2: Dyslexics show worse inhibition scores than their non-dyslexic peers, Hypothesis 1: Dyslexics show worse verbal working memory than their non-dyslexic peers, is not supported by these findings.

Verbal Working Memory.

To test hypothesis 3a: Multilingualism will moderate the relationship between dyslexia and verbal working memory, with the effect of age, sex and education accounted for, multiple regression analysis was performed. Working memory as assessed by the reverse digit span test was set as the dependent variable. All continuous predictors were mean centered. The assumptions underlying multiple linear regression were tested for all dependent variables and may be found in Appendix E, for this model none of the assumptions were violated. An overview of regression results may be found in Table 2. When entering all predictors simultaneously, none appear to be significantly predicting verbal working memory scores. Of note is the explained variance: this model only explains 6% of the variance in the outcome variable (F(5, 52) = 0.66, p = .65, R^2 = *.06,* R^2_{adj} = -.03), reflected in a negative R^2_{adj} score, indicating that the sum of the entered predictor variables are rather poorly suited to explain variation in verbal working memory scores.

Table 2.

Regression results using the backwards digit span measure as the criterion.

Predictor	*b*	*b* 95% CI [LL, UL]	*β*	*β* 95% CI [LL, UL]	*p-uncor.*
(Intercept)	5.17**	[4.49, 5.84]			<.001**
Sex	0.06	[-0.69, 0.82]	0.02	[-0.25, 0.30]	.86
Age (centered	0.04	[-0.08, 0.15]	0.09	[-0.21, 0.40]	.53
Education (centered)	0.05	[-0.14, 0.24]	0.08	[-0.23, 0.39]	.61

Predictor	*b*	*b* 95% CI [LL, UL]	*β*	*β* 95% CI [LL, UL]	*p-uncor.*
Dyslexia	-0.45	[-1.16, 0.27]	-0.17	[-0.44, 0.10]	.21
Multilingualism (centered)	0.29	[-0.70, 1.27]	0.08	[-0.21, 0.37]	.56

Model Fit	
R^2	.06
95% CI	[.00, .13]
R^2_{adj}	-0.03

Note. N=58. None of the predictors remained significant after FDR-correction. *b* represents unstandardized regression weights. *β* indicates the standardized regression weights. ** indicates $p < .01$ before FDR-correction.

To assess the impact of the interaction between dyslexia and multilingualism, an interaction term (dyslexia diagnosis X multilingualism) in addition to all previously described predictors was included in the regression analysis. Of note is the high multicollinearity found between multilingualism scores and the interaction term (see Appendix E: Multicollinearity). For the dependent variable verbal working memory a multiple linear regression sufficed. Regression results can be found in Table 3, while Figure 5 provides a visualization of the interaction between dyslexia and multilingualism regarding verbal working memory.

Table 3.

Regression results using the backwards digit span measure as the criterion, including the interaction term.

Predictor	*b*	*b* 95% CI [LL, UL]	*SE*	*β*	*β* 95% CI [LL, UL]	*p-uncor.*
(Intercept)	5.14***	[4.47, 5.82]	0.34			<.001***
Sex	0.12	[-0.65, 0.89]	0.38	0.04	[-0.24, 0.33]	.76
Age (centered)	0.04	[-0.08, 0.16]	0.06	0.10	[-0.20, 0.40]	.52
Education (centered)	0.03	[-0.17, 0.23]	0.10	0.05	[-0.27, 0.37]	.75
Dyslexia	-0.46	[-1.18, 0.26]	0.36	-0.18	[-0.45, 0.10]	.20
Multilingualism (centered)	-0.21	[-1.89, 1.46]	0.83	-0.06	[-0.56, 0.43]	.80
Interaction (centered)[a]	0.77	[-1.30, 2.85]	1.03	0.19	[-0.32, 0.69]	.46

Model Fit	
R^2	.07
95% CI	[.00,.13]
R^2_{adj}	-0.04

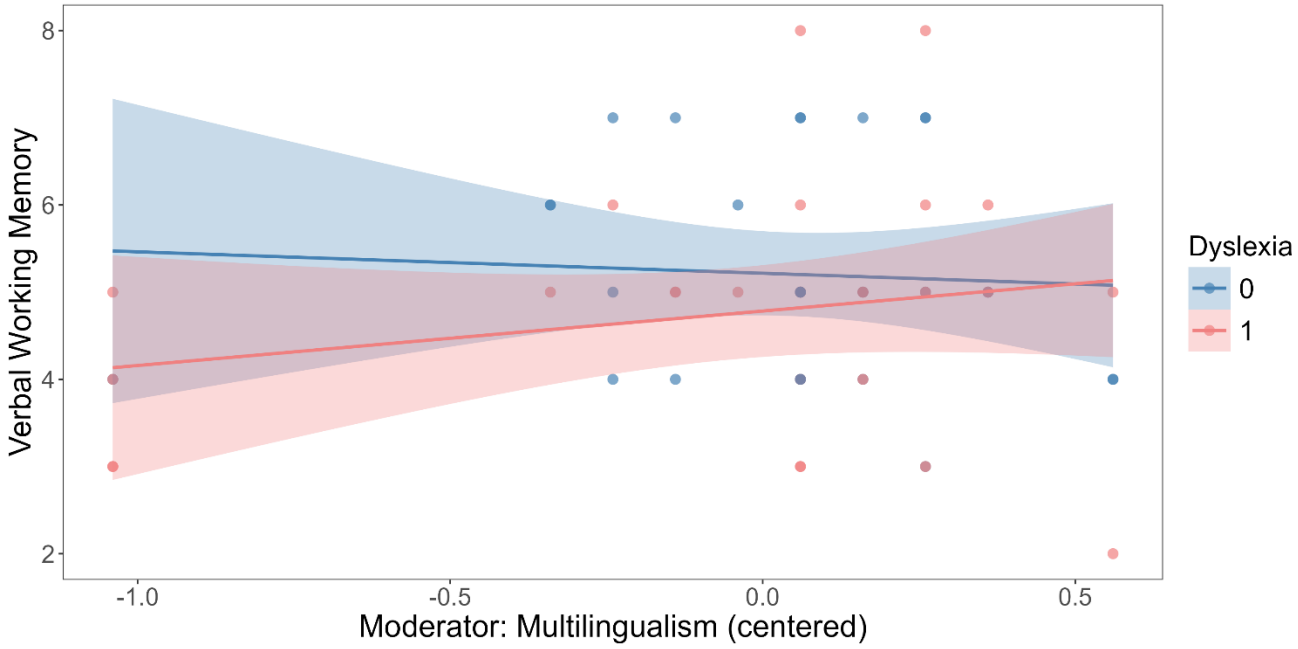
Note. N=58. *b* represents unstandardized regression weights. *β* indicates the standardized regression weights. [a] Interaction between dyslexia diagnosis and multilingualism. ** indicates $p < .01$. None of the

predictors remained significant after FDR-correction.

The interaction term (dyslexia diagnosis X multilingualism) did not significantly predict verbal working memory scores, indicating no support for Hypothesis 3a: Multilingualism moderates the relationship between dyslexia and inhibition on the behavioral level. As found for the regression excluding the interaction term, no other predictors appeared significant. Further, the increase in explained variance between the model excluding and including the interaction term was at 1%, with the overall explained variance of the interaction model being only at 7% ($F(5, 51) = 0.64$, $p = .69$, $R^2 = .07$, $R^2_{adj} = -.04$). Of note is the finding that the model including the interaction term is not significant, indicating that there is not enough evidence to conclude there to be a relationship between the predictive variables and verbal working memory. Further, R^2_{adj} decreases by .01 when including the interaction term, indicating that the inclusion of this predictor does not improve the model's predictive power. Exploratory within-group regression analyses may be found in Appendix F. Figure 5 visualizes this non-significant interaction, showing that while with increasing multilingualism scores, especially dyslexic participants appeared to gain higher scores on the verbal working memory measure, the difference in slopes between both groups are small and the 95% CI of the slopes are largely overlapping.

Figure 5.

Multilingualism scores plotted against verbal working memory scores.



Inhibition.

What becomes apparent when looking at the distribution plot of inhibition scores in Table 1 is the non-normal and slightly right-skewedness of both group distributions. In contrast to the model setting verbal working memory as the outcome variable, the assumption of multivariate normality was not met for the model predicting inhibition (See Appendix E: Multivariate Normality). Hence, a generalized linear model with a Gamma distribution and log link was used to predict inhibition scores, which does not necessitate the response variable to be normally distributed but allows it to follow a gamma-distribution (Salinas Ruíz et al., 2023). Results can be found in Table 4. Entering all predictors into the model simultaneously, only dyslexia diagnosis appears as a significant predictor for inhibition as measured by the ANT-I executive control subcomponent ($b = 0.31$, $p = .006$). As dyslexia is coded as a binary variable, the exponentiated coefficient, $e^{0.31} = 1.36$, indicates that the expected inhibition score is 36% higher when a dyslexia diagnosis is present compared to when it is absent, controlling for age, sex and education. After correcting for multiple comparisons, this finding remained significant. A likelihood ratio test comparing the main-effects model to a null model was statistically significant ($\chi^2(5) = 1.94$, $p = .04$), indicating weak evidence that the main effects improve fit over the null model.

Table 4.

Generalized linear regression results using inhibition as the criterion.

Predictor	*b*	*b* 95% CI	*β*	*β* 95% C	*p-uncor.*	*pFDR*
(Intercept)	4.03***	[3.83, 4.23]			<.001***	
Sex	-0.03	[-0.26, 0.20]	-0.01	[-0.12, 0.10]	.81	
Age (centered)	-0.01	[-0.05, 0.03]	-0.04	[-0.16, 0.10]	.55	
Education (centered)	-0.003	[-0.06, 0.06]	-0.006	[-0.14, 0.12]	.92	
Dyslexia	0.31**	[0.10, 0.53]	0.16	[0.05, 0.27]	.006**	<.05*
Multiling. (centered)	-0.16	[-0.45, 0.11]	-0.06	[-0.17, 0.04]	.28	

Fit		dF
AIC	542.68	
Null deviance	10.32	57
Residual deviance	8.38	52

Note. N=58. *b* represents unstandardized regression weights. *β* indicates the standardized regression weights. * indicates $p < .05$. ** indicates $p < .01$. * in the pFDR-column indicates significance at the .05-level after FDR-correction.

To summarize, a dyslexia diagnosis appears to be related to increased inhibition-related reaction times (as measured by the ANT-I task) but does not significantly predict verbal working memory (as measured by the backwards digit span task) when accounting for age, sex and education, while multilingualism does not predict either verbal working memory or inhibition. To assess Hypothesis 3b: Multilingualism moderates the relationship between dyslexia and inhibition on the behavioral level, a generalized linear regression including the interaction term (dyslexia diagnosis X multilingualism) was run (see Table 5). Within this model, only the presence of a dyslexia diagnosis appeared as a significant predictor for inhibition as measured by the executive control component of the ANT-I task (b = 0.32, p = .005). This finding remained significant after FDR-correction ($pFDR$ < .05). The exponentiated coefficient, $e^{0.32}$ = 1.38 indicates that the expected inhibition score is 38% higher when a dyslexia diagnosis is present, controlling for age, sex and education. The interaction term, however, appeared to be non-significant already before FDR-correction (b = -0.12, p = .70). A likelihood ratio test indicated that adding the interaction term did not significantly improve model fit over the main-effects-only model ($\chi^2(1) = 0.03$, p = 0.68), nor over the intercept-only (null) model ($\chi^2(6) = 1.97$, p = .069).

Table 5.

Generalized linear regression results using inhibition as the criterion, including the interaction term.

Predictor	*b*	*b* 95% CI	*β*	*β* 95% C	*p-uncor.*	*pFDR*
(Intercept)	4.03***	[3.83, 4.24]			<.001***	
Sex	-0.04	[-0.28, 0.19]	-0.02	[-0.13, 0.09]	.73	
Age (centered)	-0.01	[-0.05, 0.03]	-0.04	[-0.16, 0.10]	.54	
Education (centered)	0	[-0.06, 0.06]	<.001	[-0.14, 0.14]	.99	
Dyslexia	0.32**	[0.10, 0.53]	.16	[0.05, 0.27]	.005**	<.05*
Multiling. (centered)	-0.09	[-0.56, 0.36]	-0.03	[-0.22, 0.14]	.74	
Interaction (centered)	-0.12	[-0.71, 0.47]	-0.04	[-0.23, 0.15]	.70	

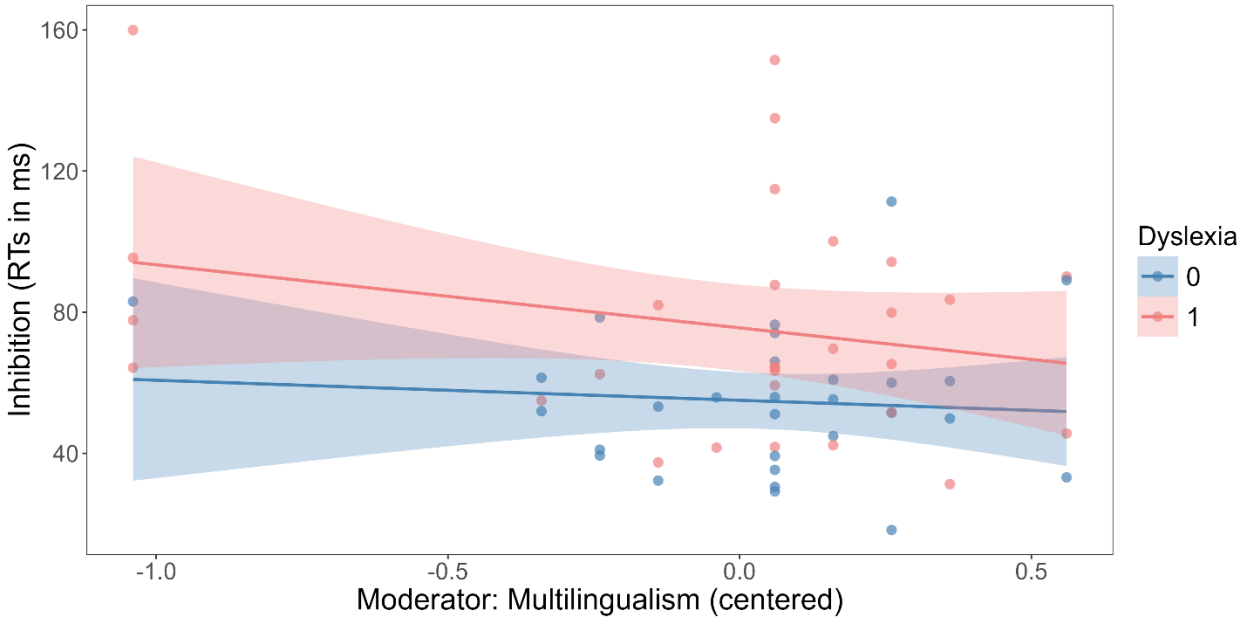
Fit		dF
AIC	544.48	
Null deviance	19.321	57
Residual deviance	8.354	52

Note. N=58. *b* represents unstandardized regression weights. *β* indicates the standardized regression weights. * indicates *p* < .05. ** indicates *p* < .01. * in the pFDR-column indicates significance at the .05-level after FDR-correction.

These findings indicate that no support could be found for Hypothesis 3b: Multilingualism moderates the relationship between dyslexia and inhibition on the behavioral level. However, the presence of a dyslexia diagnosis appeared to be significant regrading inhibition scores, even when including its interaction term with multilingualism into the model. Figure 6 visualizes the non-significant interaction between dyslexia and multilingualism. While RTs appeared to slightly decrease (indicating better inhibition performance) with increasing multilingualism scores, and the slope for dyslexic participants appeared slightly steeper than for their non-dyslexic peers, the 95% CIs of both slopes appear to overlap to a large degree.

Figure 6.

Centered multilingualism scores plotted against inhibition scores.



Note. Scores of the inhibition measure reflect reaction time differences between congruent and incongruent conditions. Entropy speaking scores, assessing degree of multilingualism, were mean centered.

To conclude, in a sample matched by age, sex and multilingualism, no support for a moderating effect of multilingualism on the relationship between dyslexia and inhibition, nor the hypothesized relationship between dyslexia and verbal working memory could be found, when age, sex, and education were accounted for within the regression models. Only a dyslexia diagnosis appeared to be related to inhibition scores, but not verbal working memory, in that the presence of a dyslexia diagnosis, the expected inhibition RT increases by 36-38%. Further, as indicated by the non-significant correlations between multilingualism and inhibition, as well as

multilingualism and verbal working memory, multilingualism did not appear to predict either outcome measure significantly. As such, no relationship between multilingualism and inhibition, or multilingualism and verbal working memory, could be found.

Exploratory Analysis: Unmatched whole-sample results.

As the matched sample only includied general speakers in both dyslexic and non-dyslexic groups, an exploratory analysis was conducted within the general sample consisting of 29 dyslexic adults as well as 122 non-dyslexic participants, including general speakers, polyglots and hyperpolyglots. Two linear regression analyses were run for the dependent variable verbal working memory. The first included Age, Sex, Education, Dyslexia and Multilingualism as predictive variables, while the second model added an interaction term (dyslexia X multilingualism). While dyslexia emerged as a significant predictor in the first model (b = -0.71, p = .02), the overall model did not significantly explain variance in verbal working memory (F(6, 145) = 1.51, p = .19, R^2 = *.05,* R^2_{adj} = .02). The second model, including the interaction term between dyslexia and multilingualism, yielded no significant predictors of verbal working memory (F(5, 144) = 1.43, p = .21, R^2 = *.06,* R^2_{adj} = .02).

Both regression analyses were further run with inhibition as the dependent variable. In the simple model including all predictors except for the interaction term between dyslexia and multilingualism, only dyslexia emerged as a significant predictor of inhibition scores (b = 14.74, p < .01). The overall model explained 7.5% of the variance in inhibition scores (F(5, 145) = 2.34, p = .04 R^2 = *.07,* R^2_{adj} = .04). In the model including the interaction term between dyslexia and multilingualism, as well as age, sex, and education, dyslexia approached significance as a predictor of inhibition scores (b = 9.53, p = .09). Further, the interaction term significantly predicted inhibition scores (b = -22.84, p = .04). The overall model explained 10% of the variance in inhibition scores (F(6, 144) = 2.69, p = .02, R^2 = *.10,* R^2_{adj} = .06).

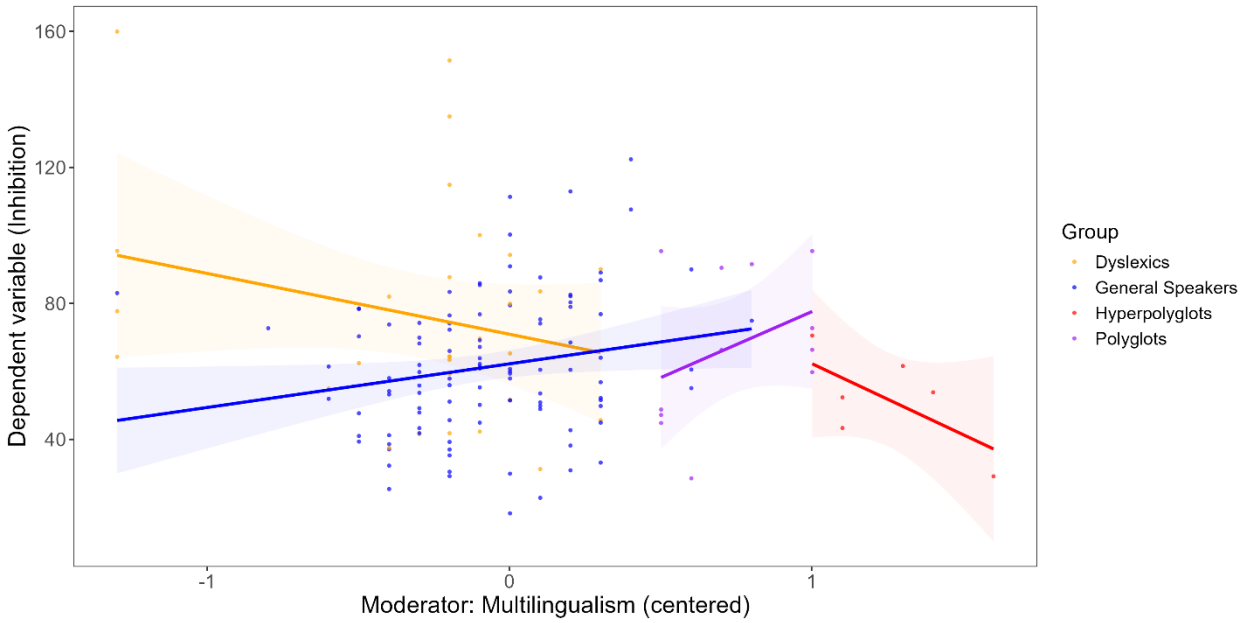
Predictor	*b*	*SE*	*p-uncor.*
(Intercept)	64.53***	3.48	<.001***
Sex	-5.04	4.09	.22
Age (centered)	-0.03	0.44	.94
Education (centered)	0.38	0.87	.66
Dyslexia	9.53	5.61	.09.
Multilingualism (centered)	4.10	5.17	.43
Interaction (centered)[a]	-22.84	11.14	.04*

Model Fit	
R^2	.10
R^2_{adj}	.06

Figure 7 visualizes this interaction between dyslexia diagnosis and spoken multilingualism. Regression lines for dyslexics (all general speakers) as well as non-dyslexic general speakers, hyperpolyglots and polyglots are highlighted separately.

Figure 7.

Visualization of the interaction between multilingualism and dyslexia per subgroup.



Note. Scores of the inhibition measure reflect reaction time differences between congruent and incongruent conditions. Entropy speaking scores, assessing degree of multilingualism, were mean centered. The dyslexic group consists of general speakers only.

Functional Connectivity.

In order to assess functional connectivity within inhibition and working memory networks at rest, first the inherent non-zero connectivity for both groups within both networks is described. Following this, group comparisons between dyslexics and non-dyslexics for each network were performed. Finally, the correlation between the interaction term (dyslexia X multilingualism) and network connectivity was assessed for each network. Throughout all connectivity analyses, CONN's "alternative settings for connection-based inferences: parametric univariate statistics"

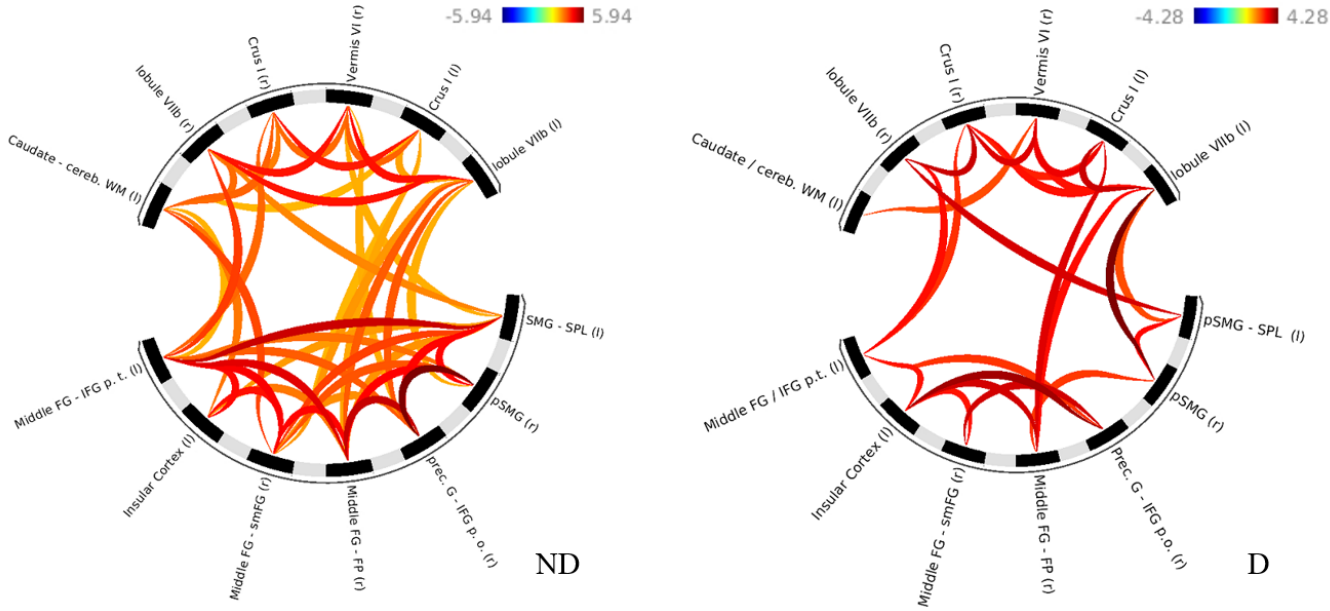
were applied, which set a connection threshold at $p < .05$ (FDR-corrected) and no cluster threshold, as cluster inference was not the focus of the present work. All analyses accounted for sex, age, education and multilingualism, with all continuous predictors being mean-centered.

Working Memory.

Inherent, non-zero connectivity at rest within the working memory network was estimated for both dyslexics and non-dyslexics. Figure 8 shows ROI-to-ROI connectivity at rest for each region of interest included in the working memory network for both dyslexics and non-dyslexics.

Figure 8.

ROI-to-ROI connectivity within the working memory network for both groups at rest.



Note. ND = non-dyslexics. D = dyslexics. (l) indicates left-hemispheric regions. (r) indicates right-hemispheric regions. Caudate -Cereb. WM = Caudate extending into Cerebellar White Matter; SMG – SPL = Supramarginal Gyrus extending into Superior Parietal Lobule; pSMG = posterior Supramarginal Gyrus; prec. G – IFG p. o. = precentral gyrus extending into IFG pars opercularis; Middle FG – FP = Middle Frontal Gyrus extending into Frontal Pole; Middle FG – SFG = Middle Frontal Gyrus extending into Superior Frontal Gyrus; Middle FG – IFG p. t. = Middle Frontal Gyrus extending into IFG pars triangularis.

As becomes apparent when looking at connectivity patterns within the working memory network, dyslexics appeared to show lower within-network connectivity than their non-dyslexic peers, as indicated by the number of connections within the network (22 significant connections for dyslexics compared to 42 significant connections for non-dyslexics). Dyslexics' strongest

connection appeared to be between the right posterior SMG extending into the anterior intraparietal sulcus and the left cerebellar lobule VIIb ($T(53) = 4.28$, $p < .001$, $pFDR = .006$), while non-dyslexics' strongest connection appeared to be between the right precentral gyrus extending into the IFG (pars opercularis) and right posterior SMG extending into the anterior intraparietal sulcus ($T(53) = 5.94$, $p < .001$, $pFDR < .001$).

Concerning connectivity patterns within networks, non-dyslexics showed 12 significant connections between cerebellar and frontal regions, while dyslexics only showed four. Regarding within-cerebellar connectivity, non-dyslexics showed nine significant connections, while dyslexics showed six. Frontal interconnectivity was reflected in nine significant connections across five frontal ROIs for non-dyslexics, while dyslexics showed six significant connections within frontal ROIs. Parietal connectivity with frontal regions was reflected in ten connections between two parietal and five frontal ROIs for non-dyslexics, while only one significant connection was found across the dyslexic group, namely between the right posterior SMG and right MFG extending into the frontal pole. Further, the ROI comprising the caudate and cerebellar white matter showed higher overall interconnectedness across non-dyslexics: three connections to cerebellar ROIs were significant, namely to left and right crus I and right lobule VIIb, while for dyslexics, only one connection to the right-hemispheric vermis VI appeared significant.

However, when comparing the average connectivity between groups, no connection reached significance when FDR-correction was applied. The strongest connectivity difference between groups was between the right precentral gyrus extending into IFG pars opercularis and the right posterior SMG extending into the anterior intraparietal sulcus, which appeared stronger for dyslexics than non-dyslexics only at the uncorrected level ($T(52) = 3.01$, $p = 0.004$, $pFDR = 0.311$). Thus, no support for the fourth hypothesis, which stated that there may be differences in connectivity between dyslexics and non-dyslexics in a network comprising regions relevant to working memory, could be found.

Inhibition.

Inherent, non-zero connectivity at rest within the working memory network was estimated for both dyslexics and non-dyslexics. Figure 9 shows ROI-to-ROI connectivity for each region of interest included in the inhibition network. As all regions were located within the right hemisphere, no hemisphere indicators were included in the ROI labels. As within the working memory network, some differences within the inhibition network between dyslexics and non-

dyslexics become apparent when looking at the number of significant connections. While within the non-dyslexic group, seven connections were significant after FDR-correction, the dyslexic group showed eleven significant connections (FDR-corrected). Dyslexics' strongest connectivity was found between the paracingulate gyrus and frontal pole ($T(53) = 4.22$, $p < .001$, $pFDR = 0.001$), while non-dyslexics' strongest connectivity was found between the posterior SMG extending into the AG and frontal pole ($T(53) = 4.41$, $p < .001$, $pFDR = 0.001$).

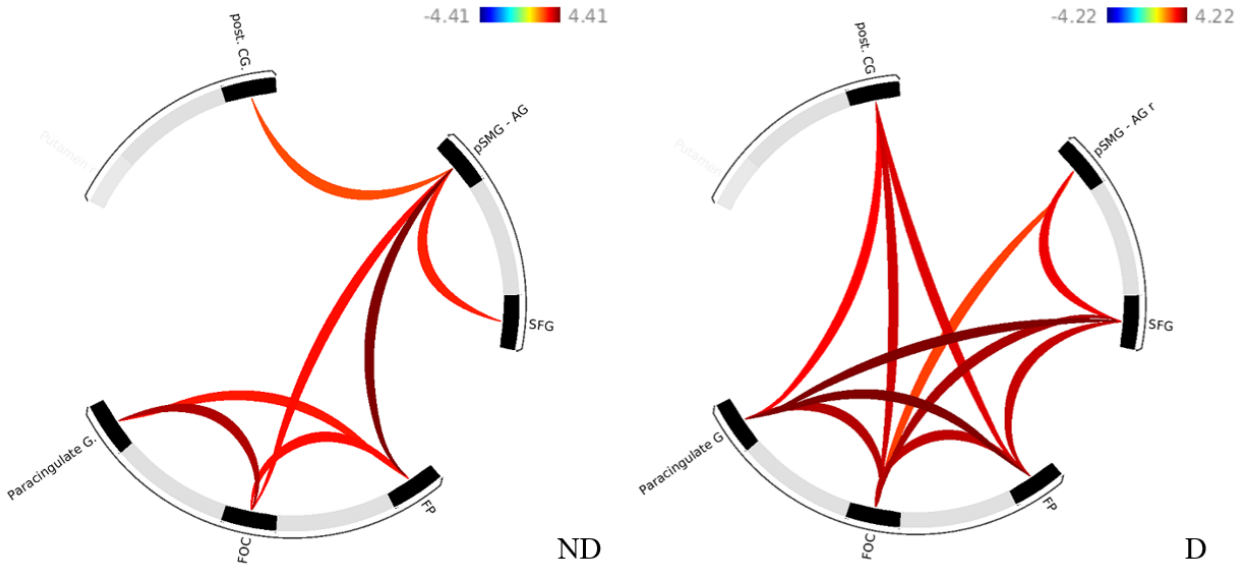
Within-frontal connectivity (including the medial frontal paracingulate gyrus) was reflected in three connections across four ROIs for the non-dyslexic group, and six connections for the dyslexic group. The medial parietal posterior cingulate gyrus showed one connection to the posterior SMG extending into AG for non-dyslexics, and three connections within the dyslexic group: one to the medial frontal paracingulate gyrus, and two to the frontal ROIs (frontal operculum cortex and frontal pole). Medial frontal connectivity was reflected in two connections for the non-dyslexic group, one from the paracingulate gyrus to the frontal operculum cortex, another one from the paracingulate gyrus to the frontal pole. For dyslexics, medial frontal connectivity was reflected in four connections to the paracingulate gyrus: one to the medial parietal posterior cingulate gyrus, and three to the frontal ROIs (SFG, frontal pole, and frontal operculum cortex). Surprisingly, the right-hemispheric putamen showed no significant connections to either parietal, frontal, medial parietal or medial frontal ROIs for either group.

However, when contrasting network connectivity between both groups to assess whether any connection would appear significantly different between dyslexics and non-dyslexics, only the connection between the paracingulate gyrus and SFG was significant at the uncorrected $p < .05$ – level, indicating it was stronger for dyslexics than non-dyslexics, but it did not survive multiple comparison correction ($T(52) = -2.11$, $p = .04$, $pFDR = .41$). Therefore, no significant differences in resting-state network connectivity between dyslexics and non-dyslexics were found for the inhibition network.

In conclusion, while differing connectivity patterns emerged between dyslexics and non-dyslexics for both inhibition and working memory networks at rest, these differences did not appear to be significant after FDR-correction.

Figure 9.

ROI-to-ROI connectivity within the inhibition network for both groups at rest.



Note. ND = non-dyslexics; D = dyslexics. All ROIs are right-hemispheric. Post.CG. = Posterior Cingulate Gyrus; pSMG – AG = posterior Supramarginal Gyrus extending into the Angular Gyrus; SFG = Superior Frontal Gyrus; FP =Frontal Pole; FOC = Frontal Operculum Cortex; Paracingulate G. = Paracingulate Gyrus.

Interaction.

Finally, hypothesis 6 (Multilingual experience modulates dyslexia-related connectivity alterations in inhibition and working memory networks at rest. Specifically, multilingual experience will be especially impactful for dyslexics in comparison to non-dyslexics at rest.) was assessed via correlation between the interaction term (dyslexia X multilingualism) and network connectivity at rest for both working memory and inhibition networks. The correlation between the interaction term and resting-state network connectivity was assessed via a model estimating all other predictive or control variables at the zero-level. Age, education and multilingualism were estimated at their mean, while dyslexia was estimated at the level of no diagnosis, and sex at the zero-level (male). Within the working memory network, no significant correlation between the interaction term and connectivity at rest could be found. The strongest connectivity related to the interaction term could be found between the right-hemispheric cerebellar Crus I and Vermis VI extending into lobule VI ($T(51) = 2.68$, $p = 0.01$, $pFDR = 0.77$), which did not survive multiple comparison correction. Within the inhibition network, the strongest connectivity related to the interaction term could be found between the right-hemispheric SFG and putamen, which did not appear significant even at the uncorrected level ($T(51) = 1.59$, $p = 0.12$, $pFDR = 0.92$).

Discussion

This study investigated behavioral and resting-state functional connectivity differences between dyslexic and non-dyslexic adults while taking into consideration the degree and impact of multilingual backgrounds. Further, the degree to which especially dyslexics would benefit from multilingual experience in their performance on inhibition and working memory tasks was assessed. Applying a data-driven approach, networks comprising regions which showed activation particularly related to both inhibition and working memory were investigated regarding their connectivity at rest. Finally, the moderating impact of multilingualism on the relationship between dyslexia and resting-state network connectivity was assessed.

No evidence in support of group differences between dyslexics and non-dyslexics could be found for the behavioral working memory measure nor resting-state network connectivity within either working memory or inhibition network. On the behavioral inhibition assessment of the ANT-I executive control task, dyslexic adults exhibited significantly poorer reaction times. This finding gives support to a small but growing body of literature finding dyslexia-related impairments across various inhibition tasks to persist into adulthood (Brosnan et al., 2002; Proulx & Elmasry, 2015; Smith-Spark et al., 2016). By evaluating differences in inhibitory control, the present study extends findings by Smith-Spark and colleagues (2016), who found impaired response inhibition for dyslexics in the form of increased error rates on a variation of a go/no-go task.

While some behavioral differences between groups could be detected, the same was not true for resting-state network connectivity. Initially, connectivity within the working memory network differed in dyslexics compared to non-dyslexics, showing reduced connectivity between regions of interest extending into the IFG and the posterior SMG extending into the SPL, as previous findings reported for phonological and executive tasks (Hoeft et al., 2011). However, these differences did not appear significant when comparing both groups directly and correcting for multiple comparisons. The same was true for connectivity patterns within the inhibition network: While dyslexics initially appeared to show higher interconnectedness within this network, especially between the right SFG and other frontal and medial frontal areas, this difference did not reach significance when controlling for multiple comparisons.

The current findings thus cannot extend the findings of task-based functional activation assessments such as by Hoeft and colleagues (2011) to resting-state functional connectivity differences between dyslexic adults and their non-dyslexic peers. As such, only the second

hypothesis was supported, which stated that dyslexic adults would perform worse regarding their reaction times on an inhibition task compared to their non-dyslexic peers.

Behavioral Findings

The absence of group differences in backward digit span performance is surprising, as working memory deficits are consistently found across the literature (Bacon et al., 2013; McLoughlin et al., 2008; Smith-Spark & Gordon, 2022). Brosnan and colleagues (2002) report consistent impairments for the forward and backward digit span task for dyslexics of varying ages, however, participants were not asked to give information on the number of languages they were speaking. The null results of the present study may potentially be explained by the linguistic backgrounds of dyslexic and non-dyslexic participants: The majority of both groups was quite multilingual. Within the dyslexic group, only four participants stated that they were monolingual, while 82.75% stated they knew two or more languages. Within the non-dyslexic group. 93.1% stated three or more languages as their background, with only one participant each stating they were monolingual or bilingual. The high degree of multilingualism in both groups may have attenuated typical group differences by enhancing working memory capacity (Calvo et al., 2016; Grundy, 2020) or compensatory mechanisms in dyslexic individuals. In addition to this, participants are likely surrounded by multiple languages in their day-to-day lives in Switzerland.

While enhanced attentional control or working memory capacity through multilingual experience may have impacted verbal working memory more directly, this benefit may not be as pronounced for inhibition, as it is a different executive function domain. A study assessing beneficial effects of bilingualism on verbal and nonverbal memory in participants showing mild cognitive impairment found better performance of bilinguals on verbal working memory tasks, while this beneficial effect on verbal recall could not be found for nonverbal memory tasks (Rosselli et al., 2019). This is in line with meta-analytic findings reporting a bilingual advantage for working memory tasks (Grundy, 2020; Hervais-Adelman et al., 2011; Monnier et al., 2022) Inhibition deficits in dyslexia may thus be more resistant to multilingual compensation or have different underlying neurocognitive bases.

While regression models did not identify multilingualism as a significant predictor of verbal working memory overall, exploratory group-specific analyses (see Appendix E) revealed divergent trends. The results of this analysis should be interpreted with caution due to their exploratory nature and lacking significance. Multilingualism showed a positive association with verbal working memory in dyslexic participants ($\beta = 0.12$, $p = .59$) and a negative association in

non-dyslexic participants (β = -0.6, p = .79). Although these effects were highly non-significant, the directionality aligns with hypotheses that multilingualism may selectively benefit individuals in which executive function is compromised, such as in children with autism spectrum disorder (Romero & Uddin, 2021), or in this case, dyslexic adults.

Considering the characteristics of the present sample, the small subgroup sizes (e.g., only four monolingual dyslexic participants) limit the generalizability of these observations. Future studies should investigate thresholds of multilingual exposure required for cognitive benefits in dyslexia, using stratified sampling across language proficiencies and age groups. On the other hand, further sample characteristics outside of multilingualism may play a role in the absence of significant differences between the impaired and typical readers. Both the dyslexic and non-dyslexic groups in the present sample were quite young (on average 23.5 and 22.9 years, respectively) and quite well-educated (on average 15.8 and 15.7 years of education, respectively). It is possible that within a bi – or multilingual society, the impact of knowing or speaking further languages in addition may not be as large, especially when task demands are low and ceiling effects due to age and education may be present (Dentella et al., 2024; Grundy & Timmer, 2017).

This may pose another possible explanation for the finding of dyslexics performing worse than non-dyslexics on the inhibition measure while no differences could be found on the measure of verbal working memory. Smith-Spark and Lewis (2023) posit that working memory deficits in dyslexia may manifest only under high cognitive load. The backward digit span may thus not have been demanding enough to allow detection of group differences in a sample which was relatively young, quite well-educated and of which the majority spoke more than two languages. Considering the finding of group differences between dyslexics and non-dyslexics on the digit span forward and backwards measure in a small sample of relatively young adults (Brosnan et al., 2002), this possibility appears less likely than the high degree of multilingualism playing a role in the present study.

Regarding the non-significant interaction terms which were added to assess potential moderating effects of multilingualism on the relationship between dyslexia and inhibition, and dyslexia and verbal working memory, there are two potential explanations. On one hand, the considerations described above regarding sample characteristics might have come into play, obstructing the detection of a potentially moderating effect of multilingualism on the relationship between dyslexia and verbal working memory as well as dyslexia and inhibition. Considering the rather small sample size, the interaction term's high multicollinearity with multilingualism scores

may have made the detection of effects additionally difficult. On the other hand, there may truly not be a beneficial moderating effect of multilingualism on the relationship between dyslexia and inhibition as well as dyslexia and verbal working memory. However, results of the exploratory analysis including polyglots and hyperpolyglots of the non-dyslexic sample indicate otherwise – here, increased multilingual proficiency affected sub-groups differently. Dyslexics appeared to benefit from higher multilingual proficiency scores similarly to non-dyslexic hyperpolyglots, while for non-dyslexic general speakers as well as polyglots increased multilingual proficiency appeared to be linked to worse inhibition scores. These results need to be considered with caution, since group comparisons may be affected by differing sample sizes as well as differing group characteristics such as multilingual proficiency. Nevertheless, future studies may re-evaluate this (likely small) relationship between dyslexia, multilingualism and inhibition within a more diverse as well as larger sample.

Resting-State Connectivity Considerations

The present study employed a data-driven approach to select relevant networks including brain regions which showed consistent activation in studies evaluating inhibition as well as working memory, to assess group differences in connectivity at rest. While all comparisons of the present analyses emerged non-significant after FDR-correction, visual inspection of within-group connectivity patterns indicate a trend within the inhibition network. Here, dyslexics showed a higher number of connections as well as stronger peak connectivity. This is in line with EEG-based findings by Fraga-Gonzáles and colleagues (2018) of more integrated, stronger but less specialized overall network connectivity at rest in dyslexics. Within the working memory network, the opposite could be found. Dyslexics appeared to show fewer significant connections as well as lower peak connectivity compared to non-dyslexics. Regarding the lack of group differences within the working memory network, findings such as the disruption of cerebellar connectivity for dyslexics during reading tasks (Turker et al., 2023), or EEG-based findings of more integrated, stronger but less specialized overall network connectivity at rest in dyslexics (Fraga-González et al., 2018) could not be extended to functional connectivity at rest as assessed by fMRI. While dyslexics did show reduced cerebellar-frontal connectivity as well as frontal-parietal connectivity when looking at the number of significant connections within the working memory network, these differences did not appear significant when directly contrasting connectivity between the dyslexic and non-dyslexic group.

Of note within the inhibition network is the lack of significant connections between the putamen and all other ROIs within this network, for both dyslexics and non-dyslexics. Activation of the putamen is linked to response inhibition specifically (Nakajima et al., 2022), and in meta-analytic findings to inhibitory processes more generally (Niendam et al., 2012). Resting-state findings showed connectivity between the putamen and motor areas, as well as the putamen and ROIs associated with cognitive control – such as the medial PFC, insula, and ACC (Jung et al., 2014). Resting-state connectivity of the putamen may thus be more easily detected in networks consisting of response inhibition-specific ROIs, or networks comprising the abovementioned ROIs, which is not the case in this study.

Interestingly, while dyslexics showed decreased task performance on the behavioral inhibition measure, these differences were not reflected in altered connectivity at rest within the inhibition network. These results are not necessarily contradictory: As demonstrated by Zhao and colleagues (2023), as well as Tuominen and colleagues (2023), task-based paradigms provide stronger and more behaviorally relevant neural signatures than resting-state approaches, making group differences easier to detect due to task-evoked network engagement. When comparing non-dyslexics and dyslexics in functional connectivity, Cheema and colleagues (2021) found domain-general resting-state network connectivity to be unrelated to actual behavioral differences between impaired and non-impaired readers. While Koyama and colleagues (2013) found persistently weaker intrinsic connectivity within a fronto-parietal attention network in dyslexic children, this finding is based on decreased connectivity between the left intraparietal sulcus (IPS) and the left MFG – a connection which was not assessed in this analysis, as the IPS did not form part of either executive function network. Future studies assessing functional connectivity related to response inhibition may include this ROI, as activation in this region is suggested to play a role in this executive function (Osada et al., 2019).

Similarly, Schurz and colleagues (2015) did find support for group differences in functional connectivity between dyslexic and non-dyslexic teenagers and young adults, highlighting reduced connectivity in dyslexic readers between the left inferior frontal gyrus and left posterior temporal areas (fusiform, inferior temporal, middle temporal, and superior temporal gyrus) even at rest. Connectivity between these areas was previously implied in reading-related processes as well as in tasks tapping working memory, such as phonological rehearsal and articulatory planning (Bulut, 2022). However, these regions of interest were not explicitly

prioritized during network selection of the present study, as the focus lied on connectivity within inhibition and working memory-related networks at rest.

Dyslexia-related altered connectivity at rest may thus be more prevalent between reading-related regions compared to inhibition or working memory-related ones. Alternatively, processes such as inhibition and working memory may not be reflected in altered connectivity at rest for dyslexics compared to non-dyslexics at all. For the present study, the low magnitude of differences in connectivity in combination with a small sample size may not have sufficed to detect connectivity differences at rest.

The present data-driven approach to generate inhibition and working memory networks yielded many advantages, such as comprehensive coverage (including regions beyond those emphasized in traditional hypotheses), higher degree of objectivity (since subjective interpretations of critical regions was not possible), and reproducibility (as Neurosynth provides standardized, publicly available maps for direct comparison across studies), however, it did have some shortcomings as well.

A notable disadvantage of this approach is the lack of task specificity: A distinction between verbal working memory and visuospatial working memory was not possible, due to coarse term granularity. Further, meta-analytic maps generated by Neurosynth may be blurred and include irrelevant voxels, reducing sensitivity to subtle effects. The right IFG - critical for domain-general inhibition (Vigneau et al., 2011) - was not explicitly included within the predefined network. Multilingualism's purported strengthening of left-right IFG connectivity (Green, 1998; Hernandez et al., 2015) might have compensated for dyslexia-related deficits, but IFG-to-IFG connectivity was not analyzed. Further considering the reported involvement of the IFG in inhibition-related processes, specifically in linguistic and non-linguistic executive control (Coderre et al., 2016), its omission may have obscured connectivity patterns specific to verbal working memory. Further, when focusing on multilingualism-related alterations in functional connectivity between dyslexic and non-dyslexic adults, connectivity between left and right IFG, as well as between inferior frontal gyrus and brain areas involved in language control such as the dlPFC and inferior parietal lobule should be assessed (Berken et al., 2016).

Recommendations for future research

While the present work aimed to assess behavioral as well as functional connectivity differences between dyslexics and non-dyslexics based on self-reported dyslexia diagnosis, a grouping approach by continuous reading and spelling scores may enable future research to

evaluate reading impairment on a more continuous basis. As remediation of deficits (both impaired reading and spelling, only impaired spelling, and presence of diagnosis but no remaining reading or spelling deficits remained) appear to impact resting-state functional connectivity (Koyama et al., 2013), future studies should aim to incorporate this differentiation.

Further, future studies may examine beneficial effects of multilingualism in dyslexic populations which do not show peak cognitive performance, such as aging or less well-educated populations, in which the beneficial effects of multilingualism may be especially observable (Kousaie et al., 2014; Stevens et al., 2023). The observation of group differences may be further facilitated by including test instruments with increasing task demands. Accuracy measures in addition to reaction time measures may provide additional information on subtle dyslexic deficits (Smith-Spark et al., 2016). Considering that dyslexia-related resting-state connectivity analyses appear to be just emerging, data-driven network identification such as applied by Finn and colleagues (2014) may provide a useful instrument in the evaluation of group differences. Alternatively, future studies may focus on the fronto-parietal attention network, in which persistent dysfunction at rest was described to characterize dyslexia (Koyama et al., 2013).

Conclusion

The present study was able to demonstrate small differences between adult dyslexics and non-dyslexic controls matched by age, sex and multilingualism, on a widely-used inhibitory control measure, extending results reporting impairments in accuracy on response inhibition (Smith-Spark et al., 2016). While no replication of results reporting impairments in verbal working memory measures such as the digit span (Brosnan et al., 2002; Smith-Spark & Gordon, 2022) could be demonstrated, this may be due to increased working memory capacity as the whole sample was characterized by rather high scores in multilingualism. Alternatively, ceiling effects may have been induced by sample characteristics such as relatively young age and high degree of education. No direct effect of multilingual proficiency nor moderating effects of multilingualism on the relationship between dyslexia and verbal working memory, or dyslexia and inhibition scores could be found. This may potentially be due to sample characteristics as well as high multicollinearity between the interaction term and multilingualism scores. Exploratory groupwise regression analyses, while tentative at best, open up discussion about the differential relationship between multilingualism and inhibition between dyslexic and non-dyslexic adults.

While previous research was able to detect atypical resting-state connectivity in dorsal and ventral pathways as well as the dorsal attention network for dyslexics (Koyama et al., 2013), this study could not extend functional connectivity differences between dyslexics and non-dyslexics to inhibition and working memory networks. Although fewer connections appeared in the number of fronto-cerebellar as well as within-cerebellar connections for dyslexics in the working memory network, these differences did not appear significant when contrasting the dyslexic group with the non-dyslexic group directly. Similar results appeared for the inhibition network: while within-frontal connectivity was reflected in a higher number of connections between regions of interest for dyslexics, these differences did not appear significant in the direct comparison to non-dyslexics. Possibly, behavioral differences between dyslexics and their non-dyslexic peers are not reflected in resting-state connectivity differences regarding inhibition, verbal working memory, and their neural correlates, in a population of highly educated, multilingual Francophones. Alternatively, future studies including larger sample sizes may be able to detect beneficial effects of multilingual proficiency for dyslexics specifically.

In conclusion, the present study aimed at assessing behavioral differences in verbal working memory and inhibition between dyslexic adults and non-dyslexic controls, while considering the multilingual backgrounds of participants. Applying a data-driven approach to inhibition and working memory network selection, resting-state ROI-to-ROI connectivity was compared between dyslexic adults and their non-dyslexic peers. While no significant differences in connectivity within these networks could be detected, the present work fills an important gap in the literature, as studies on adult dyslexia which take into account participants' language experience are few.

References

Achaa-Amankwaa, P., Kushnereva, E., Miksch, H., Stumme, J., Heim, S., & Ebersbach, M. (2023). Multilingualism is associated with small task-specific advantages in cognitive performance of older adults. *Scientific Reports*, *13*, 16912. https://doi.org/10.1038/s41598-023-43961-7

Alrwaita, N., Houston-Price, C., Meteyard, L., Voits, T., & Pliatsikas, C. (2024). Executive functions are modulated by the context of dual language use: Diglossic, bilingual and monolingual older adults. *Bilingualism: Language and Cognition*, *27*(1), 178–203. https://doi.org/10.1017/S1366728923000056

Angelides, N. H., Gupta, J., & Vickery, T. J. (2017). Associating resting-state connectivity with trait impulsivity. Social Cognitive and Affective Neuroscience, 12(6), 1001–1008. https://doi.org/10.1093/scan/nsx031

Antoniou, M. (2019). The Advantages of Bilingualism Debate. *Annual Review of Linguistics*, *5*(Volume 5, 2019), 395–415. https://doi.org/10.1146/annurev-linguistics-011718-011820

Bacon, A. M., Parmentier ,Fabrice B. R., & and Barr, P. (2013). Visuospatial memory in dyslexia: Evidence for strategic deficits. *Memory*, *21*(2), 189–209. https://doi.org/10.1080/09658211.2012.718789

Baddeley, A. (2003). Working memory and language: An overview. *Journal of Communication Disorders*, *36*(3), 189–208. https://doi.org/10.1016/S0021-9924(03)00019-4

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Berken, J. A., Chai, X., Chen, J.-K., Gracco, V. L., & Klein, D. (2016). Effects of Early and Late Bilingualism on Resting-State Functional Connectivity. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *36*(4), Article 4. https://doi.org/10.1523/JNEUROSCI.1960-15.2016

Berkes, M., & Bialystok, E. (2022). Bilingualism as a Contributor to Cognitive Reserve: What it Can do and What it Cannot do. *American Journal of Alzheimer's Disease and Other Dementias*, *37*, 15333175221091417. https://doi.org/10.1177/15333175221091417

Bialystok, E. (2015). Bilingualism and the Development of Executive Function: The Role of Attention. *Child Development Perspectives*, *9*(2), 117–121. https://doi.org/10.1111/cdep.12116

Bialystok, E., Craik, F. I. M., & Luk, G. (2012). Bilingualism: Consequences for mind and brain. *Trends in Cognitive Sciences*, *16*(4), 240–250. https://doi.org/10.1016/j.tics.2012.03.001

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859–873. https://doi.org/10.1037/0278-7393.34.4.859

Boisgueheneuc, F. du, Levy, R., Volle, E., Seassau, M., Duffau, H., Kinkingnehun, S., Samson, Y., Zhang, S., & Dubois, B. (2006). Functions of the left superior frontal gyrus in humans: a lesion study. Brain (London, England : 1878), 129(12), 3315–3328. https://doi.org/10.1093/brain/awl244

Brosnan, M., Demetre, J., Hamill, S., Robson, K., Shepherd, H., & Cody, G. (2002). Executive functioning in adults and children with developmental dyslexia. *Neuropsychologia*, *40*(12), Article 12. https://doi.org/10.1016/s0028-3932(02)00046-5

Brunamonti, E., Chiricozzi, F. R., Clausi, S., Olivito, G., Giusti, M. A., Molinari, M., Ferraina, S., & Leggio, M. (2014). Cerebellar Damage Impairs Executive Control and Monitoring of Movement Generation. *PLOS ONE*, *9*(1), e85997. https://doi.org/10.1371/journal.pone.0085997

Bulut, T. (2022). Meta-analytic connectivity modeling of the left and right inferior frontal gyri. *Cortex*, *155*, 107–131. https://doi.org/10.1016/j.cortex.2022.07.003

Butterfuss, R., & Kendeou, P. (2018). The Role of Executive Functions in Reading Comprehension. *Educational Psychology Review*, *30*(3), 801–826. https://doi.org/10.1007/s10648-017-9422-6

Calhoun, V. D., Wager, T. D., Krishnan, A., Rosch, K. S., Seymour, K. E., Nebel, M. B., Mostofsky, S. H., Nyalakanai, P., & Kiehl, K. (2017). The impact of T1 versus EPI spatial normalization templates for fMRI data analyses. *Human Brain Mapping*, *38*(11), 5331–5342. https://doi.org/10.1002/hbm.23737

Callejas, A., Lupiàñez, J., Funes, M. J., & Tudela, P. (2005). Modulations among the alerting, orienting and executive control networks. *Experimental Brain Research*, *167*(1), 27–37. https://doi.org/10.1007/s00221-005-2365-z

Callens, M., Tops, W., & Brysbaert, M. (2012). Cognitive Profile of Students Who Enter Higher Education with an Indication of Dyslexia. *PLOS ONE*, *7*(6), Article 6. https://doi.org/10.1371/journal.pone.0038081

Chang, C., Crottaz-Herbette, S., & Menon, V. (2007). Temporal dynamics of basal ganglia response and connectivity during verbal working memory. NeuroImage (Orlando, Fla.), 34(3), 1253–1269. https://doi.org/10.1016/j.neuroimage.2006.08.056

Chase, H. W., Clark, L., Sahakian, B. J., Bullmore, E. T., & Robbins, T. W. (2008). Dissociable roles of prefrontal subregions in self-ordered working memory performance. Neuropsychologia, 46(11), 2650–2661. https://doi.org/10.1016/j.neuropsychologia.2008.04.021

Cheema, K., Ostevik, A. V., Westover, L., Hodgetts, W. E., & Cummine, J. (2021). Resting-state networks and reading in adults with and without reading impairments. *Journal of Neurolinguistics*, *60*, 101016. https://doi.org/10.1016/j.jneuroling.2021.101016

Coderre, E. L., Smith, J. F., van Heuven, W. J. B., & Horwitz, B. (2016). The Functional Overlap of Executive Control and Language Processing in Bilinguals. *Bilingualism (Cambridge, England)*, *19*(3), Article 3. https://doi.org/10.1017/S1366728915000188

Comishen, K. J., & Bialystok, E. (2021). Increases in attentional demands are associated with language group differences in working memory performance. *Brain and Cognition*, *147*, 105658. https://doi.org/10.1016/j.bandc.2020.105658

Conway, T., Heilman, K. M., Gopinath, K., Peck, K., Bauer, R., Briggs, R. W., Torgesen, J. K., & Crosson, B. (2008). Neural substrates related to auditory working memory comparisons in dyslexia: An fMRI study. *Journal of the International Neuropsychological Society*, *14*(4), 629–639. https://doi.org/10.1017/S1355617708080867

Dash, T., Joanette, Y., & Ansaldo, A. I. (2022). Exploring attention in the bilingualism continuum: A resting-state functional connectivity study. *Brain and Language*, *224*, 105048. https://doi.org/10.1016/j.bandl.2021.105048

Daucourt, M. C., Schatschneider, C., Connor, C. M., Al Otaiba, S., & Hart, S. A. (2018). Inhibition, Updating Working Memory, and Shifting Predict Reading Disability Symptoms in a Hybrid Model: Project KIDS. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.00238

de Azevedo, A. F., Buchweitz, A., Esper, N. B., Portuguez, M. W., & Silva, A. D. C. (2023). Dyslexia and the perks of being bilingual: a study on the neurobiology of reading with fMRI. *Ilha Do Desterro*, *76*(3), 279–299. https://doi.org/10.5007/2175-8026.2023.e94524

de Bruin, A., Roelofs, A., Dijkstra, T., & FitzPatrick, I. (2014). Domain-general inhibition areas of the brain are involved in language switching: FMRI evidence from trilingual speakers. *NeuroImage*, *90*, 348–359. https://doi.org/10.1016/j.neuroimage.2013.12.049

DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proceedings of the National Academy of Sciences*, *116*(15), 7565–7574. https://doi.org/10.1073/pnas.1811513116

Dentella, V., Masullo, C., & Leivada, E. (2024). Bilingual disadvantages are systematically compensated by bilingual advantages across tasks and populations. *Scientific Reports*, *14*(1), 2107. https://doi.org/10.1038/s41598-024-52417-5

Deschamps, I., Baum, S. R., & Gracco, V. L. (2014). On the role of the supramarginal gyrus in phonological processing and verbal working memory: Evidence from rTMS studies. Neuropsychologia, 53(1), 39–46. https://doi.org/10.1016/j.neuropsychologia.2013.10.015

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, *64*(Volume 64, 2013), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Doust, C., Fontanillas, P., Eising, E., Gordon, S. D., Wang, Z., Alagöz, G., Molz, B., Pourcain, B. S., Francks, C., Marioni, R. E., Zhao, J., Paracchini, S., Talcott, J. B., Monaco, A. P., Stein, J. F., Gruen, J. R., Olson, R. K., Willcutt, E. G., DeFries, J. C., … Luciano, M. (2022). Discovery of 42 genome-wide significant loci associated with dyslexia. *Nature Genetics*, *54*(11), 1621–1629. https://doi.org/10.1038/s41588-022-01192-y

Doyle, C., Smeaton, A. F., Roche, R. A. P., & Boran, L. (2018). Inhibition and Updating, but Not Switching, Predict Developmental Dyslexia and Individual Variation in Reading Ability. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.00795

Dvorak, M. (2024). Inhibitory control and academic achievement – a study of the relationship between Stroop Effect and university students' academic performance. *BMC Psychology*, *12*, 498. https://doi.org/10.1186/s40359-024-01984-3

Emch, M., von Bastian, C. C., & Koch, K. (2019). Neural Correlates of Verbal Working Memory: An fMRI Meta-Analysis. *Frontiers in Human Neuroscience*, *13*, 180. https://doi.org/10.3389/fnhum.2019.00180

Espy, K. A. (2018). *Using Developmental, Cognitive, and Neuroscience Approaches To Understand Executive Control in Young Children: A Special Issue of developmental Neuropsychology*. Psychology Press.

Facoetti, A., Paganoni, P., Turatto, M., Marzola, V., & Mascetti, G. G. (2000). Visual-Spatial Attention in Developmental Dyslexia. *Cortex*, *36*(1), 109–123. https://doi.org/10.1016/S0010-9452(08)70840-2

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471–479. https://doi.org/10.1016/j.neuroimage.2005.02.004

Farah, R., Ionta, S., & Horowitz-Kraus, T. (2021). Neuro-Behavioral Correlates of Executive Dysfunctions in Dyslexia Over Development From Childhood to Adulthood. *Frontiers in Psychology*, *12*, 708863. https://doi.org/10.3389/fpsyg.2021.708863

Finn, E. S., Shen, X., Holahan, J. M., Scheinost, D., Lacadie, C., Papademetris, X., Shaywitz, S. E., Shaywitz, B. A., & Constable, R. T. (2014). Disruption of Functional Networks in Dyslexia: A Whole-Brain, Data-Driven Analysis of Connectivity. *Biological Psychiatry*, *76*(5), 397–404. https://doi.org/10.1016/j.biopsych.2013.08.031

Fostick, L., & Revah, H. (2018). Dyslexia as a multi-deficit disorder: Working memory and auditory temporal processing. *Acta Psychologica*, *183*, 19–28. https://doi.org/10.1016/j.actpsy.2017.12.010

Fraga González, G., Smit, D. J. A., van der Molen, M. J. W., Tijms, J., Stam, C. J., de Geus, E. J. C., & van der Molen, M. W. (2018). EEG Resting State Functional Connectivity in Adult Dyslexics Using Phase Lag Index and Graph Analysis. *Frontiers in Human Neuroscience*, *12*. https://doi.org/10.3389/fnhum.2018.00341

Gelman, A., Hill ,Jennifer, & and Yajima, M. (2012). Why We (Usually) Don't Have to Worry About Multiple Comparisons. *Journal of Research on Educational Effectiveness*, *5*(2), 189–211. https://doi.org/10.1080/19345747.2011.618213

Georgiou, G. K., & Das, J. P. (2018). Direct and indirect effects of executive function on reading comprehension in young adults. *Journal of Research in Reading*, *41*(2), 243–258. https://doi.org/10.1111/1467-9817.12091

Goddings, A.-L., Roalf, D., Lebel, C., & Tamnes, C. K. (2021). Development of white matter microstructure and executive functions during childhood and adolescence: A review of diffusion MRI studies. *Developmental Cognitive Neuroscience*, *51*, 101008. https://doi.org/10.1016/j.dcn.2021.101008

Gollan, T. H., Salmon, D. P., Montoya, R. I., & Galasko, D. R. (2011). Degree of bilingualism predicts age of diagnosis of Alzheimer's disease in low-education but not in highly educated Hispanics. *Neuropsychologia*, *49*(14), 3826–3830. https://doi.org/10.1016/j.neuropsychologia.2011.09.041

Gooch, D., Snowling, M., & Hulme, C. (2011). Time perception, phonological skills and executive function in children with dyslexia and/or ADHD symptoms. *Journal of Child Psychology and Psychiatry*, *52*(2), Article 2. https://doi.org/10.1111/j.1469-7610.2010.02312.x

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition*, *1*(2), Article 2. https://doi.org/10.1017/S1366728998000133

Grundy, J. G. (2020). The effects of bilingualism on executive functions: An updated quantitative analysis. *Journal of Cultural Cognitive Science*, *4*(2), 177–199. https://doi.org/10.1007/s41809-020-00062-5

Grundy, J. G., & Timmer, K. (2017). Bilingualism and working memory capacity: A comprehensive meta-analysis. *Second Language Research*, *33*(3), 325–340. https://doi.org/10.1177/0267658316678286

Guidali, G., Pisoni, A., Bolognini, N., & Papagno, C. (2019). Keeping order in the brain: The supramarginal gyrus and serial order in short-term memory. Cortex, 119, 89–99. https://doi.org/10.1016/j.cortex.2019.04.009

Gullifer, J. W., & Titone, D. (2020). Characterizing the social diversity of bilingualism using language entropy. *Bilingualism: Language and Cognition*, *23*(2), 283–294. https://doi.org/10.1017/S1366728919000026

Hachmann, W. M., Bogaerts, L., Szmalec, A., Woumans, E., Duyck, W., & Job, R. (2014). Short-term memory for order but not for item information is impaired in developmental dyslexia. *Annals of Dyslexia*, *64*(2), Article 2. https://doi.org/10.1007/s11881-013-0089-5

Henson, R. N. A., Buechel, C., Josephs, O., & Friston, K. J. (1999). The slice-timing problem in event-related fMRI. *NeuroImage*, *9*, 125.

Herman, A. M., Critchley, H. D., & Duka, T. (2019). Binge drinking is associated with attenuated frontal and parietal activation during successful response inhibition in fearful context. The European Journal of Neuroscience, 50(3), 2297–2310. https://doi.org/10.1111/ejn.14108

Hervais-Adelman, A. G., Moser-Mercer, B., & Golestani, N. (2011). Executive Control of Language in the Bilingual Brain: Integrating the Evidence from Neuroimaging to Neuropsychology. *Frontiers in Psychology*, *2*. https://doi.org/10.3389/fpsyg.2011.00234

Higo, T., Mars, R. B., Boorman, E. D., Buch, E. R., & Rushworth, M. F. S. (2011). Distributed and causal influence of frontal operculum in task control. Proceedings of the National Academy of Sciences - PNAS, 108(10), 4230–4235. https://doi.org/10.1073/pnas.1013361108

Hoeft, F., McCandliss, B. D., Black, J. M., Gantman, A., Zakerani, N., Hulme, C., Lyytinen, H., Whitfield-Gabrieli, S., Glover, G. H., Reiss, A. L., & Gabrieli, J. D. E. (2011). Neural systems predicting long-term outcome in dyslexia. *Proceedings of the National Academy of Sciences*, *108*(1), 361–366. https://doi.org/10.1073/pnas.1008950108

Horowitz-Kraus, T. (2014). Pinpointing the deficit in executive functions in adolescents with dyslexia performing the Wisconsin card sorting test: An ERP study. *Journal of Learning Disabilities*, *47*(3), 208–223. https://doi.org/10.1177/0022219412453084

Ishigami, Y., Eskes, G. A., Tyndall, A. V., Longman, R. S., Drogos, L. L., & Poulin, M. J. (2016). The Attention Network Test-Interaction (ANT-I): Reliability and validity in healthy older adults. *Experimental Brain Research*, *234*(3), 815–827. https://doi.org/10.1007/s00221-015-4493-4

Jalali-Moghadam, N., & Kormi-Nouri, R. (2015). The role of executive functions in bilingual children with reading difficulties. *Scandinavian Journal of Psychology*, *56*(3), 297–305. https://doi.org/10.1111/sjop.12198

Januszko, P., Gmaj, B., Piotrowski, T., Kopera, M., Klimkiewicz, A., Wnorowska, A., Wołyńczyk-Gmaj, D., Brower, K. J., Wojnar, M., & Jakubczyk, A. (2021). Delta resting-state functional connectivity in the cognitive control network as a prognostic factor for maintaining abstinence: An eLORETA preliminary study. Drug and Alcohol Dependence, 218, 108393. https://doi.org/10.1016/j.drugalcdep.2020.108393

John, A., Stott, J., & Richards, M. (2022). Childhood reading problems and cognitive ageing across mid to later life. *J Epidemiol Community Health*, *76*(1), 67–74. https://doi.org/10.1136/jech-2020-215735

Jolles, D. D., van Buchem, M. A., Crone, E. A., & Rombouts, S. A. R. B. (2013). Functional brain connectivity at rest changes after working memory training. Human Brain Mapping, 34(2), 396–406. https://doi.org/10.1002/hbm.21444

Jung, W. H., Jang, J. H., Park, J. W., Kim, E., Goo, E.-H., Im, O.-S., & Kwon, J. S. (2014). Unravelling the Intrinsic Functional Organization of the Human Striatum: A Parcellation and Connectivity Study Based on Resting-State fMRI. PloS One, 9(9), e106768. https://doi.org/10.1371/journal.pone.0106768

Kałamała, P., Szewczyk, J., Chuderski, A., Senderecka, M., & Wodniecka, Z. (2020). Patterns of bilingual language use and response inhibition: A test of the adaptive control hypothesis. *Cognition*, *204*, 104373. https://doi.org/10.1016/j.cognition.2020.104373

Kepinska, O., Caballero, J., Oliver, M., Marks, R. A., Haft, S. L., Zekelman, L., Kovelman, I., Uchikoshi, Y., & Hoeft, F. (2023). Language combinations of multilinguals are reflected in their first-language knowledge and processing. *Scientific Reports*, *13*(1), 1947. https://doi.org/10.1038/s41598-023-27952-2

Korucuoglu, O., Harms, M. P., Astafiev, S. V., Golosheykin, S., Kennedy, J. T., Barch, D. M., & Anokhin, A. P. (2021). Test-Retest Reliability of Neural Correlates of Response Inhibition and Error Monitoring: An fMRI Study of a Stop-Signal Task. *Frontiers in Neuroscience*, *15*. https://doi.org/10.3389/fnins.2021.624911

Kousaie, S., Sheppard, C., Lemieux, M., Monetta, L., & Taler, V. (2014). Executive function and bilingualism in young and older adults. *Frontiers in Behavioral Neuroscience*, *8*, 250. https://doi.org/10.3389/fnbeh.2014.00250

Koyama, M. S., Di Martino, A., Kelly, C., Jutagir, D. R., Sunshine, J., Schwartz, S. J., Castellanos, F. X., & Milham, M. P. (2013). Cortical signatures of dyslexia and remediation: An intrinsic functional connectivity approach. *PloS One*, *8*(2), e55454. https://doi.org/10.1371/journal.pone.0055454

Laird, A. R., Fox, P. M., Eickhoff, S. B., Turner, J. A., Ray, K. L., McKay, D. R., Glahn, D. C., Beckmann, C. F., Smith, S. M., & Fox, P. T. (2011). Behavioral Interpretations of Intrinsic Connectivity Networks. *Journal of Cognitive Neuroscience*, *23*(12), 4022–4037. https://doi.org/10.1162/jocn_a_00077

Lefavrais, P. (1967). *Manuel du test de l'alouette: Test d'analyse de la lecture et de la dyslexie* (2e ed). Centre de Psychologie Appliquée. https://cir.nii.ac.jp/crid/1130282273074354816

Lehto, J. E., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, *21*(1), 59–80. https://doi.org/10.1348/026151003321164627

Li, Y., Li, J., Yang, Y., & Bi, H.-Y. (2023). Disruption of dynamic functional connectivity in children with developmental dyslexia. *Language, Cognition and Neuroscience*, *38*(5), 621–635. https://doi.org/10.1080/23273798.2022.2129084

Li, Y., Yang, L., Li, L., Xie, Y., & Fang, P. (2022). The resting-state cerebro-cerebellar function connectivity and associations with verbal working memory performance. Behavioural Brain Research, 417, 113586. https://doi.org/10.1016/j.bbr.2021.113586

Liu, L., Li, H., Zhang, M., Wang, Z., Wei, N., Liu, L., Meng, X., & Ding, G. (2016). Aberrant topologies and reconfiguration pattern of functional brain network in children with second language reading impairment. *Developmental Science*, *19*(4), 657–672. https://doi.org/10.1111/desc.12440

Lonergan, A., Doyle, C., Cassidy, C., Mahon, S. M., Roche, R. A. P., Boran, L., & Bramham, J. (2019). A meta-analysis of executive functioning in dyslexia with consideration of the impact of comorbid ADHD. *Journal of Cognitive Psychology*. https://www.tandfonline.com/doi/abs/10.1080/20445911.2019.1669609

Long, J., Song, X., Wang, Y., Wang, C., Huang, R., & Zhang, R. (2022). Distinct neural activation patterns of age in subcomponents of inhibitory control: A fMRI meta-analysis. Frontiers in Aging Neuroscience, 14, 938789. https://doi.org/10.3389/fnagi.2022.938789

Luo, L., Craik, F. I. M., Moreno, S., & Bialystok, E. (2013). Bilingualism interacts with domain in a working memory task: Evidence from aging. *Psychology and Aging*, *28*(1), 28–34. https://doi.org/10.1037/a0030875

McLoughlin, D., Fitzgibbon, G., & Young, V. (2008). *Adult Dyslexia: Assessment, Counselling and Training*. John Wiley & Sons.

Melloni, C. (2021). Phonological Awareness across Child Populations: How Bilingualism and Dyslexia Interact. *Languages*, *6*(1), 39. https://doi.org/10.3390/languages6010039

Menon, V., & D'Esposito, M. (2022). The role of PFC networks in cognitive control and executive function. *Neuropsychopharmacology*, *47*(1), 90–103. https://doi.org/10.1038/s41386-021-01152-w

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167–202. https://doi.org/10.1146/annurev.neuro.24.1.167

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The Unity and Diversity of Executive Functions and Their Contributions to Complex "Frontal Lobe" Tasks: A Latent Variable Analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Monnier, C., Boiché, J., Armandon, P., Baudoin, S., & Bellocchi, S. (2022). Is bilingualism associated with better working memory capacity? A meta-analysis. *International Journal of Bilingual Education and Bilingualism*, *25*(6), 2229–2255. https://doi.org/10.1080/13670050.2021.1908220

Moore, A. B., Li, Z., Tyner, C. E., Hu, X., & Crosson, B. (2013). Bilateral basal ganglia activity in verbal working memory. Brain and Language, 125(3), 316–323. https://doi.org/10.1016/j.bandl.2012.05.003

Moojen, S. M. P., Gonçalves, H. A., Bassôa, A., Navas, A. L., de Jou, G., & Miguel, E. S. (2020). Adults with dyslexia: How can they achieve academic success despite impairments in basic reading and writing abilities? The role of text structure sensitivity as a compensatory skill. *Annals of Dyslexia*, *70*(1), 115–140. https://doi.org/10.1007/s11881-020-00195-w

Nakajima, K., Osada, T., Ogawa, A., Tanaka, M., Oka, S., Kamagata, K., Aoki, S., Oshima, Y., Tanaka, S., & Konishi, S. (2022). A causal role of anterior prefrontal-putamen circuit for response inhibition revealed by transcranial ultrasound stimulation in humans. Cell Reports (Cambridge), 40(7), 111197. https://doi.org/10.1016/j.celrep.2022.111197

Nergård-Nilssen, T., & Hulme, C. (2014). Developmental Dyslexia in Adults: Behavioural Manifestations and Cognitive Correlates. *Dyslexia*, *20*(3), 191–207. https://doi.org/10.1002/dys.1477

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective, & Behavioral Neuroscience*, *12*(2), 241–268. https://doi.org/10.3758/s13415-011-0083-5

Nieto-Castanon, A. (2020a). FMRI minimal preprocessing pipeline. In *Handbook of functional connectivity Magnetic Resonance Imaging methods in CONN* (pp. 3–16). Hilbert Press.

Nieto-Castanon, A. (2020b). General Linear Model. In *Handbook of functional connectivity Magnetic Resonance Imaging methods in CONN* (pp. 62–82). Hilbert Press.

Nieto-Castanon, A. (2022). *Preparing fMRI Data for Statistical Analysis* (No. arXiv:2210.13564). arXiv. https://doi.org/10.48550/arXiv.2210.13564

Nieto-Castanon, A., & Whitfield-Gabrieli, S. (2022). *CONN functional connectivity toolbox: RRID SCR_009550, release 22* (22nd ed.). Hilbert Press. https://doi.org/10.56441/hilbertpress.2246.5840

Nissim, N. R., O'Shea, A. M., Bryant, V., Porges, E. C., Cohen, R., & Woods, A. J. (2017). Frontal Structural Neural Correlates of Working Memory Performance in Older Adults. *Frontiers in Aging Neuroscience*, *8*, 328. https://doi.org/10.3389/fnagi.2016.00328

Nowrangi, M. A., Lyketsos, C., Rao, V., & Munro, C. A. (2014). Systematic Review of Neuroimaging Correlates of Executive Functioning: Converging Evidence From Different Clinical Populations. *The Journal of Neuropsychiatry and Clinical Neurosciences*, *26*(2), 114–125. https://doi.org/10.1176/appi.neuropsych.12070176

Osada, T., Ohta, S., Ogawa, A., Tanaka, M., Suda, A., Kamagata, K., Hori, M., Aoki, S., Shimo, Y., Hattori, N., Shimizu, T., Enomoto, H., Hanajima, R., Ugawa, Y., & Konishi, S. (2019). An Essential Role of the Intraparietal Sulcus in Response Inhibition Predicted by Parcellation-Based Network. The Journal of Neuroscience, 39(13), 2509–2521. https://doi.org/10.1523/JNEUROSCI.2244-18.2019

Ozernov-Palchik, O., Beach, S. D., Brown, M., Centanni, T. M., Gaab, N., Kuperberg, G., Perrachione, T. K., & Gabrieli, J. D. E. (2022). Speech-specific perceptual adaptation deficits in children and adults with dyslexia. *Journal of Experimental Psychology. General*, *151*(7), 1556–1572. https://doi.org/10.1037/xge0001145

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232–258. https://doi.org/10.1016/j.cogpsych.2012.12.002

Pelham, S. D., & Abrams, L. (2014). Cognitive advantages and disadvantages in early and late bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(2), 313–325. https://doi.org/10.1037/a0035224

Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., & Nichols, T. E. (2011). *Statistical Parametric Mapping: The Analysis of Functional Brain Images*. Elsevier.

Prior, A., & MacWhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism (Cambridge, England)*, *13*(2), 253–262. https://doi.org/10.1017/S1366728909990526

Privitera, A. J., Zhou, Y., Xie, X., & Huang, D. (2022). Inhibitory Control Predicts Academic Performance Beyond Fluid Intelligence and Processing Speed in English-Immersed Chinese High Schoolers. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *44*(44). https://escholarship.org/uc/item/77r925hr

Proulx, M. J., & Elmasry, H.-M. (2015). Stroop interference in adults with dyslexia. *Neurocase*, *21*(4), 413–417. https://doi.org/10.1080/13554794.2014.914544

Rampinini, A., Balboni, I., Golestani, N., & Berthele, R. (2024). A behavioural exploration of language aptitude and experience, cognition and more using Graph Analysis. *Brain Research*, *1842*, 149109. https://doi.org/10.1016/j.brainres.2024.149109

Reiter, A., Tucha, O., & Lange, K. W. (2005). Executive functions in children with dyslexia. *Dyslexia*, *11*(2), 116–131. https://doi.org/10.1002/dys.289

Relyea, J. E., Cho, E., & Zagata, E. (2023). First-grade multilingual students' executive function profiles and links to English reading achievement and difficulties: A person-centered latent profile analysis. *Annals of Dyslexia*, *73*(1), 29–52. https://doi.org/10.1007/s11881-022-00272-2

Rodriguez-Fornells, A., Lugt, A. van der, Rotte, M., Britti, B., Heinze, H.-J., & Münte, T. F. (2005). Second Language Interferes with Word Production in Fluent Bilinguals: Brain Potential and Functional Imaging Evidence. *Journal of Cognitive Neuroscience*, *17*(3), 422–433. https://doi.org/10.1162/0898929053279559

Romero, C., & Uddin, L. Q. (2021). Bilingualism, Executive Function, and the Brain: Implications for Autism. *Neurobiology of Language*, *2*(4), 513–531. https://doi.org/10.1162/nol_a_00057

Rogalsky, C. (2008). Broca's area, sentence comprehension, and working memory: an fMRI study. Frontiers in Human Neuroscience, 2, 14. https://doi.org/10.3389/neuro.09.014.2008

Rosselli, M., Loewenstein, D. A., Curiel, R. E., Penate, A., Torres, V. L., Lang, M., Greig, M. T., Barker, W. W., & Duara, R. (2019). Effects of Bilingualism on Verbal and Nonverbal Memory Measures in Mild Cognitive Impairment. Journal of the International Neuropsychological Society, 25(1), 15–28. https://doi.org/10.1017/S135561771800070X

Rubia, K., Smith, A. B., Brammer, M. J., Toone, B., & Taylor, E. (2005). Abnormal Brain Activation During Inhibition and Error Detection in Medication-Naive Adolescents With ADHD. The American Journal of Psychiatry, 162(6), 1067–1075. https://doi.org/10.1176/appi.ajp.162.6.1067

Ryan, J. J., Townsend ,James M., & and Kreiner, D. S. (2014). Comparison of Oral, Written, and Pointing Responses to WAIS-IV Digit Span. *Applied Neuropsychology: Adult*, *21*(2), 94–97. https://doi.org/10.1080/09084282.2012.753076

Salinas Ruíz, J., Montesinos López, O. A., Hernández Ramírez, G., & Crossa Hiriart, J. (2023). Generalized Linear Models. In *Generalized Linear Mixed Models with Applications in*

Agriculture and Biology (pp. 43–84). Springer, Cham. https://doi.org/10.1007/978-3-031-32800-8_2

Salminen, T., Forlim, C. G., Schubert, T., & Kühn, S. (2020). Dual n-back training improves functional connectivity of the right inferior frontal gyrus at rest. Scientific Reports, 10(1), 20379–10. https://doi.org/10.1038/s41598-020-77310-9

Schaum, M., Pinzuti, E., Sebastian, A., Lieb, K., Fries, P., Mobascher, A., Jung, P., Wibral, M., & Tüscher, O. (2021). Right inferior frontal gyrus implements motor inhibitory control via beta-band oscillations in humans. *eLife*, *10*, e61679. https://doi.org/10.7554/eLife.61679

Schmitt, S. A., Geldhof, G. J., Purpura, D. J., Duncan, R., & McClelland, M. M. (2017). Examining the relations between executive function, math, and literacy during the transition to kindergarten: A multi-analytic approach. *Journal of Educational Psychology*, *109*(8), 1120–1140. https://doi.org/10.1037/edu0000193

Schroeder, S. R., Marian, V., Shook, A., & Bartolotti, J. (2016). Bilingualism and Musicianship Enhance Cognitive Control. *Neural Plasticity*, *2016*(1), 4058620. https://doi.org/10.1155/2016/4058620

Schurz, M., Wimmer, H., Richlan, F., Ludersdorfer, P., Klackl, J., & Kronbichler, M. (2015). Resting-State and Task-Based Functional Brain Connectivity in Developmental Dyslexia. *Cerebral Cortex*, *25*(10), 3502–3514. https://doi.org/10.1093/cercor/bhu184

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, *27*(3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Simioni, A. C., Dagher, A., & Fellows, L. K. (2017). Effects of levodopa on corticostriatal circuits supporting working memory in Parkinson's disease. Cortex, 93, 193–205. https://doi.org/10.1016/j.cortex.2017.05.021

Sladky, R., Friston, K. J., Tröstl, J., Cunnington, R., Moser, E., & Windischberger, C. (2011). Slice-timing effects and their correction in functional MRI. *NeuroImage*, *58*(2), 588–594. https://doi.org/10.1016/j.neuroimage.2011.06.078

Smith-Spark, J. H., & Gordon, R. (2022). Automaticity and Executive Abilities in Developmental Dyslexia: A Theoretical Review. *Brain Sciences*, *12*(4), Article 4. https://doi.org/10.3390/brainsci12040446

Smith-Spark, J. H., Henry, L. A., Messer, D. J., Edvardsdottir, E., & Zięcik, A. P. (2016). Executive functions in adults with developmental dyslexia. *Research in Developmental Disabilities*, *53–54*, 323–341. https://doi.org/10.1016/j.ridd.2016.03.001

Smith-Spark, J. H., Henry, L. A., Messer, D. J., & Zięcik, A. P. (2017). Verbal and Non-verbal Fluency in Adults with Developmental Dyslexia: Phonological Processing or Executive Control Problems? *Dyslexia*, *23*(3), 234–250. https://doi.org/10.1002/dys.1558

Smith-Spark, J. H., & Lewis, E. G. (2023). Lived Experiences of Everyday Memory in Adults with Dyslexia: A Thematic Analysis. *Behavioral Sciences*, *13*(10), 840. https://doi.org/10.3390/bs13100840

Spielberg, J. M., Miller, G. A., Heller, W., & Banich, M. T. (2015). Flexible brain network reconfiguration supporting inhibitory control. *Proceedings of the National Academy of Sciences*, *112*(32), 10020–10025. https://doi.org/10.1073/pnas.1500048112

St Clair-Thompson, H. L., & Allen, R. J. (2013). Are forward and backward recall the same? A dual-task study of digit recall. *Memory & Cognition*, *41*(4), 519–532. https://doi.org/10.3758/s13421-012-0277-2

Stanovich, K. E. (1988). The right and wrong places to look for the cognitive locus of reading disability. *Annals of Dyslexia*, *38*(1), 154–177. https://doi.org/10.1007/BF02648254

Stasenko, A., Matt, G. E., & Gollan, T. H. (2017). A relative bilingual advantage in switching with preparation: Nuanced explorations of the proposed association between bilingualism and task switching. *Journal of Experimental Psychology: General*, *146*(11), 1527–1550. https://doi.org/10.1037/xge0000340

Stevens, W. D., Khan, N., Anderson, J. A., Grady, C. L., & Bialystok, E. (2023). A neural mechanism of cognitive reserve: The case of bilingualism. *NeuroImage*, *281*. https://doi.org/10.1016/j.neuroimage.2023.120365

Stoodley, C. J., & Schmahmann, J. D. (2009). Functional topography in the human cerebellum: A meta-analysis of neuroimaging studies. NeuroImage (Orlando, Fla.), 44(2), 489–501. https://doi.org/10.1016/j.neuroimage.2008.08.039

Struys, E., Duyck, W., & Woumans, E. (2018). The Role of Cognitive Development and Strategic Task Tendencies in the Bilingual Advantage Controversy. *Frontiers in Psychology*, *9*, 1790. https://doi.org/10.3389/fpsyg.2018.01790

Swanson, H. L., & Hsieh, C.-J. (2009). Reading Disabilities in Adults: A Selective Meta-Analysis of the Literature. *Review of Educational Research*, *79*(4), 1362–1390. https://doi.org/10.3102/0034654309350931

Swanson, H. L., Orosco, M. J., & Kudo, M. (2017). Does Growth in the Executive System of Working Memory Underlie Growth in Literacy for Bilingual Children With and Without

Reading Disabilities? *Journal of Learning Disabilities*, *50*(4), 386–407. https://doi.org/10.1177/0022219415618499

Teubner-Rhodes, S. (2020). Cognitive Persistence and Executive Function in the Multilingual Brain During Aging. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.568702

Theodoridou, D., Christodoulides, P., Zakopoulou, V., & Syrrou, M. (2021). Developmental Dyslexia: Environment Matters. *Brain Sciences*, *11*(6), 782. https://doi.org/10.3390/brainsci11060782

Timmann, D., & Daum, I. (2007). Cerebellar contributions to cognitive functions: A progress report after two decades of research. *The Cerebellum*, *6*(3), 159–162. https://doi.org/10.1080/14734220701496448

Tomiyama, H., Murayama, K., Nemoto, K., Tomita, M., Hasuzawa, S., Mizobe, T., Kato, K., Matsuo, A., Ohno, A., Kan, M., Togao, O., Hiwatashi, A., Ishigami, K., & Nakao, T. (2023). Posterior cingulate cortex spontaneous activity associated with motor response inhibition in patients with obsessive-compulsive disorder: A resting-state fMRI study. Psychiatry Research. Neuroimaging, 334, 111669. https://doi.org/10.1016/j.pscychresns.2023.111669

Trecy, M. P., Steve, M., & Martine, P. (2013). Impaired short-term memory for order in adults with dyslexia. *Research in Developmental Disabilities*, *34*(7), 2211–2223. https://doi.org/10.1016/j.ridd.2013.04.005

Trinczer, I. L., Dankner, Y., Frances-Israeli, S., Okamoto, Y. A., Clark, D., & Shalev, L. (2024). The Contribution of Sustained Attention and Response Inhibition to Reading Comprehension Among Japanese Adolescents. *Children*, *11*(10), 1245. https://doi.org/10.3390/children11101245

Tuominen, J., Specht, K., Vaisvilaite, L., & Zeidman, P. (2023). An information-theoretic analysis of resting-state versus task fMRI. *Network Neuroscience*, *7*(2), 769–786. https://doi.org/10.1162/netn_a_00302

Turker, S., Kuhnke, P., Jiang, Z., & Hartwigsen, G. (2023). Disrupted network interactions serve as a neural marker of dyslexia. *Communications Biology*, *6*(1), 1–17. https://doi.org/10.1038/s42003-023-05499-2

Utts, J. M. (1982). The rainbow test for lack of fit in regression. *Communications in Statistics - Theory and Methods*, *11*(24), 2801–2815. https://doi.org/10.1080/03610928208828423

Van Reybroeck, M., & De Rom, M. (2020). Children with dyslexia show an inhibition domain-specific deficit in reading. *Reading and Writing*, *33*(4), 907–933. https://doi.org/10.1007/s11145-019-09986-z

Vartanian, O., Replete, V., Saint, S. A., Lam, Q., Forbes, S., Beaudoin, M. E., Brunyé, T. T., Bryant, D. J., Feltman, K. A., Heaton, K. J., McKinley, R. A., Van Erp, J. B. F., Vergin, A., & Whittaker, A. (2022). What Is Targeted When We Train Working Memory? Evidence From a Meta-Analysis of the Neural Correlates of Working Memory Training Using Activation Likelihood Estimation. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.868001

Vasic, N., Lohr, C., Steinbrink, C., Martin, C., & Wolf, R. C. (2008). Neural correlates of working memory performance in adolescents and young adults with dyslexia. *Neuropsychologia*, *46*(2), 640–648. https://doi.org/10.1016/j.neuropsychologia.2007.09.002

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, *45*(1), 2–40. https://doi.org/10.1046/j.0021-9630.2003.00305.x

Vender, M., Krivochen, D. G., Phillips, B., Saddy, D., & Delfitto, D. (2019). Implicit Learning, Bilingualism, and Dyslexia: Insights From a Study Assessing AGL With a Modified Simon Task. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.01647

Vincent, J. L., Kahn, I., Snyder, A. Z., Raichle, M. E., & Buckner, R. L. (2008). Evidence for a frontoparietal control system revealed by intrinsic functional connectivity. Journal of neurophysiology, 100(6), 3328–3342. https://doi-org.uaccess.univie.ac.at/10.1152/jn.90355.2008

Wang, L.-C., Tasi, H.-J., & Yang, H.-M. (2012). Cognitive inhibition in students with and without dyslexia and dyscalculia. *Research in Developmental Disabilities*, *33*(5), 1453–1461. https://doi.org/10.1016/j.ridd.2012.03.019

Whitfield-Gabrieli, S., & Nieto-Castanon, A. (2012). Conn: A functional connectivity toolbox for correlated and anticorrelated brain networks. *Brain Connectivity*, *2*(3), 125–141. https://doi.org/10.1089/brain.2012.0073

Willcutt, E. G., Pennington ,Bruce F., Olson ,Richard K., Chhabildas ,Nomita, & and Hulslander, J. (2005). Neuropsychological Analyses of Comorbidity Between Reading Disability and Attention Deficit Hyperactivity Disorder: In Search of the Common Deficit. *Developmental Neuropsychology*, *27*(1), 35–78. https://doi.org/10.1207/s15326942dn2701_3

Wolf, R. C., Sambataro, F., Lohr, C., Steinbrink, C., Martin, C., & Vasic, N. (2010). Functional brain network abnormalities during verbal working memory performance in

adolescents and young adults with dyslexia. *Neuropsychologia*, *48*(1), 309–318. https://doi.org/10.1016/j.neuropsychologia.2009.09.020

Xia, L. (2021). *Effects of language learning and bilingualism on executive functions: Influence of exposure, experience and linguistic distance*. https://doi.org/10.7488/era/1048

Yang, S., Yang, H., & Hartanto, A. (2019). The effects of script variation, literacy skills, and immersion experience on executive attention: A comparison of matched monoscriptal and biscriptal bilinguals. *Bilingualism: Language and Cognition*, *22*(1), 142–156. https://doi.org/10.1017/S1366728917000633

Yuan, Q., Li, H., Du, B., Dang, Q., Chang, Q., Zhang, Z., Zhang, M., Ding, G., Lu, C., & Guo, T. (2023). The cerebellum and cognition: Further evidence for its role in language control. *Cerebral Cortex*, *33*(1), 35–49. https://doi.org/10.1093/cercor/bhac051

Zhang, M., Li, J., Chen, C., Xue, G., Lu, Z., Mei, L., Xue, H., Xue, F., He, Q., Chen, C., Wei, M., & Dong, Q. (2014). Resting-state functional connectivity and reading abilities in first and second languages. *NeuroImage*, *84*, 546–553. https://doi.org/10.1016/j.neuroimage.2013.09.006

Zhang, R., Geng, X., & Lee, T. M. C. (2017). Large-scale functional neural network correlates of response inhibition: an fMRI meta-analysis. Brain Structure and Function, 222(9), 3973–3990. https://doi.org/10.1007/s00429-017-1443-x

Zhao, W., Makowski, C., Hagler, D. J., Garavan, H. P., Thompson, W. K., Greene, D. J., Jernigan, T. L., & Dale, A. M. (2023). Task fMRI paradigms may capture more behaviorally relevant information than resting-state functional connectivity. *NeuroImage*, *270*, 119946. https://doi.org/10.1016/j.neuroimage.2023.119946

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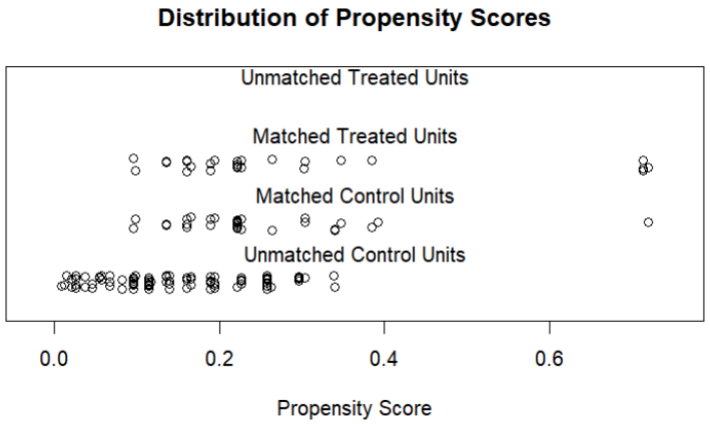
List of Abbreviations

Abbreviation	Definition
ACC	Anterior Cingulate Cortex
ACG	Anterior Cingulate Gyrus
AG	Angular Gyrus
ART	Artifact Detection Tools
BOLD	Blood Oxygenation Level Dependent
Cereb. WM	Cerebellar White Matter
CSF	Cerebrospinal Fluid
D	Dyslexics
dlPFC	Dorsolateral Prefrontal Cortex
FOC	Frontal Operculum Cortex
FP	Frontal Pole
GLM	General Linear Model
IFG	Inferior Frontal Gyrus
IFG p.o.	Inferior Frontal Gyrus, pars opercularis
IFG p.t.	Inferior Frontal Gyrus, pars triangularis
Medial FG	Medial Frontal Gyrus
MFG	Middle Frontal Gyrus
MNI space	Montreal Neurological Institute space
ND	Non-dyslexics
PCA	Principal Component
PFC	Prefrontal Cortex
pFDR	p-value corrected for False Discovery Rate
post. CG	Posterior Cingulate Gyrus
pSMG	Posterior Supramarginal Gyrus
ROI	Region of Interest
RT	Reaction Time
SFG	Superior Frontal Gyrus
SMA	Supplementary Motor Area
SMG	Supramarginal Gyrus
SPL	Superior Parietal Lobule
SPM	Statistical Parametric Mapping

Appendices

Appendix A: Propensity Score Distribution




```
Summary of Balance for All Data:
           Means Treated      Means Control Std. Mean Diff. Var. Ratio eCDF Mean eCDF Max
distance          0.2812         0.1737          0.5712     3.1304    0.1752   0.3204
age              23.5241        24.8042         -0.3216     0.4154    0.0462   0.1144
sex               0.6552         0.6750         -0.0417          .    0.0198   0.0198
entr_speak        1.0000         1.3767         -0.8305     0.9289    0.1368   0.3037

Summary of Balance for Matched Data:
           Means Treated      Means Control Std. Mean Diff. Var. Ratio eCDF Mean eCDF Max
distance          0.2812         0.2444          0.1957     2.4148    0.0146   0.1379
age              23.5241        22.9000          0.1568     2.2016    0.0650   0.1724
sex               0.6552         0.6207          0.0725          .    0.0345   0.0345
entr_speak        1.0000         1.0793         -0.1749     2.0964    0.0082   0.1034
           Std. Pair Dist.
distance             0.1963
age                  0.6766
sex                  0.2176
entr_speak           0.1749
```

```
Sample Sizes:
          Control Treated
All           120      29
Matched        29      29
Unmatched      91       0
Discarded       0       0
```

Appendix B: Neurosynth clusters and their overlap with brain regions

Working Memory

Cluster	Voxels	MAX	MAX X	MAX Y	MAX Z	COG X	COG Y	COG Z	Max-Activation	Center of Gravity COG
106	2875	10.7	67	77	49	64.5	71.2	53	69% Middle Frontal Gyrus (l)	38% Middle Frontal Gyrus (l)
									7% IFG, pars triangularis (l)	6% IFG, pars opercularis (l)
105	2082	12.5	64	38	58	60.7	34.6	58.5	30% post. Supramarginal Gyrus (l)	39% Superior parietal lobule (l)
									22% Superior Parietal Lobule (l)	11% Angular gyrus (l)
									20% Angular Gyrus (l)	9% post. Supramarginal gyrus (l)
104	2037	12.3	30	65	64	36.7	68	61.6	50% Middle Frontal Gyrus (r)	No overlap with Harvard-Oxford
									16% Superior Frontal gyrus (r)	Cortical Structural Atlas regions.
103	1824	11.5	24	40	58	28.5	36	58.5	31% post. Supramarginal gyrus (r)	30% Sup. Parietal Lobule (r)
										20% Angular Gyrus (r)
102	1621	11.8	24	80	52	25.1	80.3	46.7	52% Middle frontal Gyrus (r)	18% Frontal Pole (r)
									24% Frontal Pole (r)	13% Middle Frontal Gyrus (r)
101	287	7.52	29	30	21	29.4	32.1	20.4	90% Right Crus I*	69% Right Crus I*
									10% Right Lobule VI*	31% Right Lobule VI*
100	223	5.74	18	68	43	21.1	67.1	48.6	37% Precentral Gyrus (r)	41% Precentral Gyrus (r)
									36% IFG, pars opercularis (r)	27% IFG, pars opercularis (r)
99	168	6.73	60	75	37	59.9	74.1	36.1	62% Insular Cortex (l)	47% Insular Cortex (l)
98	115	6.38	62	31	21	62.3	32.4	20.6	99% left Crus I*	82% left Crus I*
										18% Left Lobule VI*
97	108	5.36	42	27	24	43.9	24.8	24.9	51% Vermis VI (r)*	73% Vermis VI (r)*
									36% Right Lobule VI*	8% Vermis Crus II (r)*
96	61	6.03	54	63	44	52.9	63	42.9	Harvard-Oxford Subcortical Atlas**	Identical to MAX activation
									94% left cerebral white matter	

Cluster	Voxels	MAX	MAX X	MAX Y	MAX Z	COG X	COG Y	COG Z	Max-Activation	Center of Gravity COG
									6% left caudate	
95	54	5.61	30	28	11	30.6	27.1	10.4	72% Right VIIb*	75% Right VIIb*
									18% Right Crus II*	15% Right VIIa*
									5% Right VIIIa*	10% Right Crus II*
94	50	5.3	62	29	10	61.6	28	10.9	65% Left VIIb*	63% Left Crus II*
									35% Left Crus II*	37% Left VIIb*

Note. "Cluster" indicates the cluster number. "Voxels" indicates the number of voxels within the cluster. "MAX" indicates the maximum z-statistic within the cluster. "MAX X, MAX Y, MAX Z" indicate the coordinates of the maximum statistic. "COG X, COG Y, COGZ", show the center of gravity coordinates of the cluster, representing the spatial average of the cluster voxels weighted by their intensities. All labels reported are according to the Harvard-Oxford Cortical Structural Atlas for both maximal activation coordinates and center of gravity coordinates and show the percentage of overlap with the clusters' coordinates. *.Cerebellar regions are labeled according to the Cerebellar Atlas in MNI52 space after normalization with FLIRT. ** no overlap with cortical regions according to the Harvard-Oxford Cortical Structural Atlas was found, so the Harvard-Oxford Subcortical Structural Atlas was consulted instead.

Inhibition

Cluster	Voxels	MAX	MAX X	MAX Y	MAX Z	COG X	COG Y	COG Z	MAX activation	Center of Gravity (COG)
58	297	8.28	23	72	34	25.2	71.6	32.1	31% Frontal Operculum Cortex	60% Insular Cortex
									18% Insular Cortex	20% Frontal Orbital Cortex
									16% Frontal Orbital Cortex	
57	171	7.91	14	40	53	15.7	41.1	52.9	47% post. supramarginal Gyrus	44% post. Supramarginal Gyrus
									41% Angular Gyrus	26% Angular gyrus
56	92	6.52	28	89	50	29.3	88.5	50.5	72% Frontal Pole	81% Frontal Pole
55	82	6	42	73	55	42.3	72.5	54.8	55%Paracingulate Gyrus	55%Paracingulate Gyrus
									30% anterior Cingulate Gyrus	30% Cingulate Gyrus
54	75	6.06	45	51	51	43.6	52.3	50.7	83% Cingulate Gyrus, post.	83% post. Cingulate Gyrus
										10%anterior cingulate gyrus
53	27	5.42	37	72	69	37.4	71	67.9	48% Sup. Frontal Gyrus	62% sup. Frontal gyrus
52	21	5.21	31	66	37	32.3	66	36.8	97% Right Putamen	100% Right Putamen

Note. All regions of interest are localized in the right hemisphere. “Cluster” indicates the cluster number. “Voxels” indicates the number of voxels within the cluster. “MAX” indicates the maximum z-statistic within the cluster. “MAX X, MAX Y, MAX Z” indicate the coordinates of the maximum statistic. “COG X, COG Y, COGZ”, show the center of gravity coordinates of the cluster, representing the spatial average of the cluster voxels weighted by their intensities. All labels reported are according to the Harvard-Oxford Cortical Structural Atlas for both maximal activation coordinates and center of gravity coordinates and show the percentage of overlap with the clusters’ coordinates.

Appendix C. Neurosynth working memory network and their overlap with working memory

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
Caudate – cereb. WM	Caudate extending into cerebellar white matter	Bilateral involvement of the caudate in encoding processes of a verbal working memory task (Moore et al., 2013) Activation of the caudate during encoding, maintenance and response phase of a Sternberg task (Chang et al., 2007)	Altered basal ganglia-cerebellar white matter tracts correlate with WM performance (Goddings et al., 2021) Strength of connectivity between caudate and right fronto-parietal network related to better performance on working memory tasks in Parkinson's disease patients (Simioni et al., 2019)	Fronto-basal-ganglia network related to executive language control in bilinguals (Hervais-Adelman et al., 2011). Caudate part of a domain-general cognitive control network (Niendam et al., 2012). Caudate part of fronto-parietal Network (Menon & D'Esposito)
SMG	Supramarginal gyrus extending into superior parietal lobule	Involvement of the SMG in verbal working memory in an rTMS study (Deschamps et al., 2014) SMG as key region for retaining serial order independent of item information across short-term		Ventral attention network (Menon & D'Esposito, 2022) Activation of right SMG in inhibition-related tasks (Niendam et al., 2012)

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
		memory tasks (Guidali et al., 2019)		
pSMG	Posterior supramarginal gyrus			Ventral attention network (Menon & D'Esposito, 2022) Activation of right SMG in inhibition-related tasks (Niendam et al., 2012)
Precentral G – IFG p. o.	Precentral gyrus extending into IFG pars opercularis	Less surface area of IFG p.o. related to worse verbal working memory scores in structural MRI (Nissim et al., 2017) IFG pars opercularis is implicated in inhibitory control (Fan et al., 2015; Laird et al., 2011)	Demanding short-term memory training (n-back task) increases connectivity of right IFG with default mode network (Salminen et al., 2020)	Precentral G part of Domain-general cognitive control network (Niendam et al., 2012) IFG part of ventral attention network (Menon & D'Esposito, 2022)
Middle FG - FP	Middle frontal gyrus extending into frontal pole	Middle Frontal Gyrus showed sign. Activation in inhibition and working memory in a meta-analysis (Niendam et al., 2012)	Functional connectivity at rest of Middle FG to frontoparietal network (SFG, paracingulate gyrus, ACC) increased after	Part of Fronto-parietal control network, involved in executive control (Vincent et al., 2008). MFG part of Fronto-parietal network (Menon & D'Esposito).

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
		Left Middle frontal gyrus involved in retrieving processes of verbal working memory tasks (Moore et al., 2013)	verbal working memory training (Jolles et al., 2013)	
Middle FG - SFG	Middle frontal gyrus extending into superior frontal gyrus	SFG (posterior and lateral) was found to form key component in neural WM network in a lesion study (Boisgueheneuc et al., 2006). Working memory training decreases activation in middle and superior frontal gyri (Vartanian et al., 2022). In dyslexics vs. controls: Activation increases with working memory demand in the left SFG, while decreased activation was found in the middle FG (Vasic et al., 2008).	Functional connectivity at rest of Middle FG to frontoparietal network (SFG, paracingulate gyrus, ACC) increased after verbal working memory training (Jolles et al., 2013)	MFG part of Fronto-parietal network (Menon & D'Esposito). SFG part of domain-general executive control network (Niendam et al., 2012)

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
		Left SFG shows significant activation across working memory tasks (Niendam et al., 2012).		
Middle FG – IFG p.o.	Middle frontal gyrus extending into IFG pars triangularis	Impairment on spatial working memory tasks in patients with frontal lesions, specifically within the IFG – p.o. (Chase et al., 2008) Greater activation in IFG p.o. under high processing load conditions in verbal task (Rogalsky, 2008)	Functional connectivity at rest of Middle FG to frontoparietal network (SFG, paracingulate gyrus, ACC) increased after verbal working memory training (Jolles et al., 2013)	IFG is implicated in cognitive control and inhibition (Niendam et al., 2012). IFG part of ventral attention network (Menon & D'Esposito, 2022).
	Cerebellar regions	Review: Evidence for cerebellar involvement in mediation of working memory (Timman & Daum, 2007). Meta-analytic activation likelihood estimation(ALE): activation peaks in Lobule VI and Crus I for language and	Increased functional connectivity at rest between the right lobule VI and right posterior cingulate cortex, as well as right anterior cingulate cortex, while decreased connectivity was found between lobule VI and bilateral SFG.	Right-lateralized cerebellar contribution to verbal working memory (Emch et al., 2019)

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
		verbal working memory (Stoodley & Schmahmann, 2009)	Functional connectivity findings related to performance on an N-back task (Li et al., 2022).	

Neurosynth inhibition network and its overlap with inhibitory processes

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
Post.CG	Posterior cingulate gyrus	Activation of post.CG (among other ROIs) in healthy participants during unsuccessful inhibition compared to successful stop trials (Rubia et al., 2005)	Decreased amplitude of low-frequency fluctuations in the post. CG and impaired response inhibition (Tomiyama et al., 2023)	
pSMG – AG	Posterior supramarginal gyrus extending into angular gyrus	Meta-analytic report of AG activation across cognitive inhibition tasks; SMG activation across response		SMG part of ventral attention network (Menon & D'Esposito, 2022)

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
		inhibition tasks (Long et al., 2022). Right SMG showed activation in a meta-analysis across inhibition tasks (Niendam et al., 2012).		
SFG	Superior frontal gyrus	Meta-analytic report of SFG activation across cognitive inhibition tasks (Long et al., 2022) SFG part of network which shows increased connectivity during higher inhibitory demand (Spielberg et al., 2015). SFG showed activation in a meta-analysis across inhibition tasks (Niendam et al., 2012).		SFG part of prefrontal network relevant during higher inhibitory demands (Spielberg et al., 2015). SFG part of domain-general executive control network (Niendam et al., 2012).
FP	Frontal pole	Left FP increasingly activated in successful response inhibition in participants with		

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
		increased alcohol consumption compared to non-drinkers (Herman et al., 2019)		
FOC	Frontal operculum cortex	Frontal operculum showed higher activation during selective attention; General involvement in cognitive control (Higo et al., 2011)	Resting-state lagged phase synchronization between anterior insula cortex/frontal operculum and right inferior frontal junction increased in the delta band in alcohol-abstinent participants compared to relapsing participants. Right frontoinsular connectivity related to lower behavioral impulsivity (Januszko et al., 2021)	Part of cingulo-opercular network (Menon & D'Esposito, 2022).
Paracingulate G.	Paracingulate gyrus	Right Paracingulate G. consistently activated across response inhibition tasks (Zhang et al., 2017)		
Putamen	Putamen	Involved in response inhibition (Nakajima et al., 2022).	Resting-state connectivity between putamen and middle	

Label	ROIs	Task-based evidence	Resting-state evidence	Part of known networks
		Activation of Putamen related to inhibition (Niendam et al., 2012)	orbitofrontal cortex related to impulsivity (Angelides et al., 2017)	

Appendix D. Correlation Table including FDR-correction

Variables		Age	Education	Reading	Spelling	Multiling	Verbal_WM
Education	**r**	**.3558**					
	p	0.0061					
	pFDR	*0.0214*					
Reading	**r**	**.1637**	**0.2681**				
	p	0.2195	0.0418				
	pFDR	*0.3545*	*0.0799*				
Spelling	**r**	**-.0144**	**0.3292**	**0.7116**			
	p	0.9145	0.0116	0.0000			
	pFDR	*0.9145*	*0.0349*	*0.0000*			
Multilingualism	**r**	**-.1016**	**0.2812**	**0.0536**	**0.2910**		
	p	0.4481	0.0325	0.6895	0.0267		
	pFDR	*0.5535*	*0.0745*	*0.7239*	*0.0701*		
Verbal_WM	**r**	**0.0946**	**0.1412**	**0.4257**	**0.4548**	**0.1179**	
	p	0.4799	0.2903	0.0009	0.0003	0.3781	
	pFDR	*0.5590*	*0.4355*	*0.0045*	*0.0025*	*0.0745*	
Inhibition	**r**	**-.0892**	**-0.1249**	**- 0.3639**	**- 0.4534**	**-0.2233**	**- 0.2768**
	p	0.5057	0.3503	0.0050	0.0004	0.0920	0.0355
	pFDR	*0.5590*	*0.4904*	*0.0209*	*0.0025*	*0.0745*	*0.0745*

Appendix F. Exploratory Groupwise Regression Results

Within-group regression models setting verbal working memory as the dependent variable.

Regression parameters within the non-dyslexic group.

```
lm(formula = Verbal_WM ~ Sex + Age_c + Educ_c + Multiling_c +
    1, data = dys0)

Residuals:
    Min      1Q  Median      3Q     Max
-2.0027 -0.9824 -0.2627  1.1675  1.9739

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  5.36808    0.40790  13.160 1.81e-12 ***
Sex         -0.24173    0.55178  -0.438    0.665
Age_c       -0.01257    0.11926  -0.105    0.917
Educ_c      -0.18226    0.19612  -0.929    0.362
Multiling_c -0.22132    0.82799  -0.267    0.792
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.294 on 24 degrees of freedom
Multiple R-squared:  0.05989,  Adjusted R-squared:  -0.0968
F-statistic: 0.3822 on 4 and 24 DF,  p-value: 0.8191
```

Regression parameters within the non-dyslexic group.

```
Call:
lm(formula = Verbal_WM ~ Sex + Age_c + Educ_c + Multiling_c +
    1, data = dys1)

Residuals:
     Min       1Q   Median       3Q      Max
-2.65122 -0.94409  0.07098  0.53939  2.88256

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  4.69747    0.44898  10.462 2.02e-10 ***
Sex          0.08879    0.56105   0.158    0.876
Age_c        0.06729    0.06915   0.973    0.340
Educ_c       0.11695    0.11973   0.977    0.338
Multiling_c  0.35266    0.64609   0.546    0.590
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.375 on 24 degrees of freedom
Multiple R-squared:  0.1492,   Adjusted R-squared:  0.007428
F-statistic: 1.052 on 4 and 24 DF,  p-value: 0.4013
```

Appendix E. Linear Regression: Assumption Checks

Linearity

Rainbow Test (Utts, 1982).

Working Memory, no interaction.

Rain = 0.73362, df1 = 29, df2 = 23, p-value = 0.7868

Working Memory, incl. interaction term:

Rain = 0.7068, df1 = 29, df2 = 22, p-value = 0.8112

Inhibition, no interaction:

Rain = 0.531, df1 = 29, df2 = 23, p-value = 0.9462

Inhibition, incl. interaction term:

Rain = 0.50283, df1 = 29, df2 = 22, p-value = 0.9583

Homoscedasticity

Breusch-Pagan Test -> no evidence of heteroscedasticity.

```
> bptest(Inh)

        studentized Breusch-Pagan test

data:  Inh
BP = 2.5033, df = 5, p-value = 0.776

> bptest(Inh_interaction)

        studentized Breusch-Pagan test

data:  Inh_interaction
BP = 3.5541, df = 6, p-value = 0.7368

> bptest(WM)

        studentized Breusch-Pagan test

data:  WM
BP = 6.453, df = 5, p-value = 0.2646

> bptest(WM_interaction)

        studentized Breusch-Pagan test

data:  WM_interaction
BP = 6.422, df = 6, p-value = 0.3776
```

Multicollinearity

Multicollinearity is assessed via the variance Inflation Factor (VIF). For Models Including interaction terms, this assumption is not met, even when interaction terms are centered.

Working Memory

Sex	Age_c	Educ_c	Dyslexia	Multiling_c
1.051082	1.253551	1.307058	1.022636	1.158479

Working Memory + Interaction

Sex	Age_c	Educ_c	Dyslexia	Multiling_c	Interaction_c
1.087255	1.255718	1.393056	1.025199	15.010486	15.393048

Inhibition

Sex	Age_c	Educ_c	Dyslexia	Multiling_c
1.051082	1.253551	1.307058	1.022636	1.158479

Inhibition + Interaction.

Sex	Age_c	Educ_c	Dyslexia	Multiling_c	Interaction_c
1.087255	1.255718	1.393056	1.025199	15.010486	15.393048

Multivariate normality

Shapiro-Wilk test.

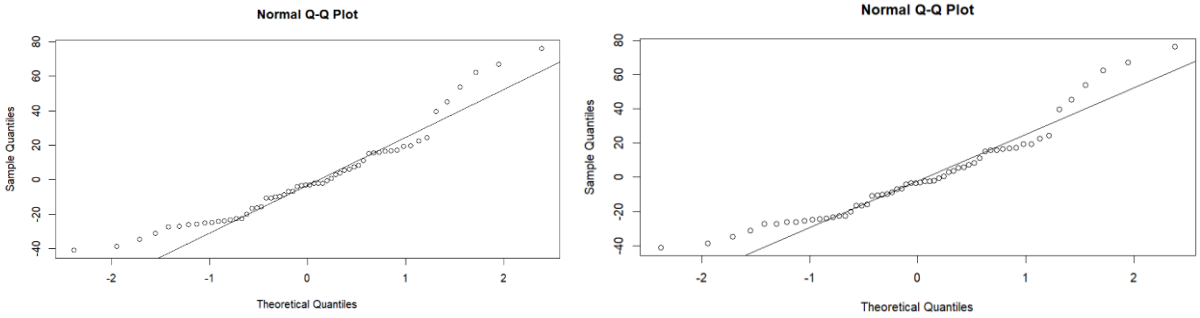
Verbal Working Memory, no interaction: W = 0.98054, p-value = 0.475

Verbal Working memory, incl. interaction W = 0.98022, p-value = 0.4611

➔ A model setting working memory as the DV fulfills the assumption of normality.

Inhibition, no interaction: W = 0.92857, p-value = 0.002118

Inhibition, incl. interaction: W = 0.93449, p-value = 0.003749



Inhibition set as the DV does not fulfill this assumption (Shapiro-Wilk test p-statistic <.05), therefore a generalized linear model may be more fitting.