

**Investigating the Role of Lexical Stress and Its  
Relationship to Phonological Abilities in Developmental  
Dyslexia: Experimental Evidence from Italian**

Doctoral thesis for obtaining the academic degree Doctor of Philosophy (Dr. phil.)

submitted by

**Marina Roberta Rossi**

At the

Universität  
Konstanz



Faculty of Humanities

Department of Linguistics

Konstanz, 2025

Day of oral examination: 23.06.2025

First Referee: Prof. Dr. Tamara Rathcke (University of Konstanz)

Second Referee: Prof. Dr. Tanja Kupisch (Lund University / University of Konstanz)

Third Referee: Prof. Dr. Paolo Mairano (Université de Tours)

## Abstract (English)

**Background:** Phonological deficits are among the most consistently reported impairments in Developmental Dyslexia (DD). However, their nature and underlying factors remain debated. One proposed explanation is reduced acoustic sensitivity to lexical stress, which could hinder phonological encoding and phoneme access. Yet, empirical findings remain inconsistent, likely due to methodological variability across studies. Given the frequent cognitive deficits in DD, an alternative explanation suggests that cognitive mediation may play a central role, with phonological impairments arising from deficient cognitive mechanisms that restrict access to otherwise spared phonological representations. Understanding the interplay between phonological processing and lexical stress sensitivity is crucial for clinical advancements, particularly in both diagnosis and intervention, and provides key insights into the relationship between spoken and written language.

**Objective:** This thesis investigated whether lexical stress processing is impaired in DD, leading to disruptions in segmental processing and phoneme access, or whether phonological deficits stem from cognitive mediation deficits that restrict access to intact phonological representations. The thesis focused on the Italian language, which is more transparent and exhibits distinct acoustic cues underlying lexical stress compared to English—a language that has been more extensively examined in the dyslexia literature. This contrast offered an opportunity to evaluate the cross-linguistic generalizability of findings related to dyslexia-associated deficits in lexical stress processing and phonological processing.

**Method:** To account for potential developmental compensation mechanisms and age-related changes associated with adulthood in dyslexia, we recruited two groups differing in their proximity to adulthood. A total of 40 adolescents with DD and 30 typically developing (TD) adolescents, along with 28 children with DD and 29 TD children, completed a phoneme monitoring task to assess implicit acoustic sensitivity to prominence in phoneme identification. Adolescents completed the task first in Study 1, while children were administered a simplified version in Study 3. Lexical stress sensitivity was further assessed in adolescents in Study 2 using a sensorimotor synchronization task, in which participants were instructed to tap in alignment with the perceived beat of spoken sentences. In contrast, children's lexical stress sensitivity was evaluated in Study 4 through a perceptual identification task that required them to distinguish between two Italian minimal pairs differing in lexical stress along a continuum, such as *papa* ['papa] “pope” vs. *papà* [pa'pa] “dad”. Both tasks were selected for their reduced metalinguistic component. Pupillometry was recorded during phoneme identification in children, as—unlike behavioural measures—it provides an implicit,

objective index of online phonological access by being sensitive to both phonological and cognitive processing, thereby minimizing false negatives. Despite its potential, this cutting-edge method has rarely been applied to the study of DD. All participants underwent a cognitive assessment. Comorbid dyscalculia was retained as an inclusion criterion due to its non-linguistic nature, though it was controlled for throughout the analysis.

**Results:** Findings from Studies 1 and 3, which employed phoneme monitoring tasks, indicated significant group-level differences in the phoneme identification performance across both cohorts, which could not be explained by inherently fragile lexical stress representations. Conversely, phonological identification differences between individuals with DD and their TD peers, regardless of age, appeared to be modulated by cognitive resources. Among TD adolescents, phonological identification rates were higher when attention-shifting ability was strong and lower when attention-shifting scores were weak. In contrast, this relationship was not observed in individuals with DD, whose performance remained consistently low, irrespective of attention-shifting ability. Additionally, cognitive resources contributed to group-level variations in children's pupillometric responses during distractor processing in the phoneme monitoring task. Studies 2 and 4 further confirmed the comparability of lexical stress representations across cohorts. Specifically, both adolescent groups demonstrated similar alignment to weak and strong syllables in the sensorimotor synchronization task of Study 2. In parallel, the categorical perception curves for lexical stress observed in Study 4 were consistent across children.

**Conclusion:** Overall, this research thesis confirmed that phonological and possibly lexical stress representations remain intact in individuals with DD throughout late childhood and adolescence. However, access to these representations appears to be compromised, likely due to an imbalance between stronger and weaker cognitive resources—an interaction that requires further empirical validation. Rather than reflecting comprehensive phonological and lexical stress deficits, difficulties in DD seem to involve specific subdomains of phonological and prosodic competence, further corroborating the multicomponential nature of these domains, with awareness being highly interconnected with the cognitive domain. Although interconnected, segmental and prosodic domains seem to develop independently and exhibit notable cross-language differences, reaching an adult-like form only in late adulthood. Therefore, the potential contributing factors of language transparency variability, along with SES and reading exposure, should be considered and incorporated into future research to better understand their role in phonological processing in DD.

## **Abstract (German)**

### **Hintergrund:**

Phonologische Defizite gehören zu den am häufigsten berichteten Beeinträchtigungen bei der Lese- und Schreibschwäche (LSS), doch ihre genaue Natur und die zugrunde liegenden Faktoren sind umstritten. Eine mögliche Erklärung für diese phonologischen Defizite ist eine Beeinträchtigung der Sensitivität für den lexikalischen Akzent, die wiederum die phonologische Kodierung sowie den Zugriff auf Phoneme beeinträchtigen könnte. Allerdings sind die empirischen Befunde hierzu uneinheitlich, was vermutlich auf methodologische Unterschiede zwischen Studien zurückzuführen ist. Angesichts der häufig auftretenden kognitiven Defizite bei LSS wird alternativ angenommen, dass kognitive Vermittlungsprozesse eine zentrale Rolle spielen, indem phonologische Beeinträchtigungen auf Defizite in kognitiven Mechanismen zurückzuführen sind, die den Zugriff auf ansonsten intakte phonologische Repräsentationen einschränken. Das Verständnis der Wechselwirkung zwischen phonologischer Verarbeitung und Sensitivität für lexikalischen Akzent ist entscheidend für klinische Fortschritte, insbesondere im Hinblick auf Diagnose und Therapie von Lese- und Schreibschwierigkeiten, und liefert wesentliche Erkenntnisse über die Beziehung zwischen gesprochener und geschriebener Sprache.

### **Zielsetzung:**

Diese Dissertation hatte zum Ziel zu untersuchen, ob die Verarbeitung von lexikalischem Akzent bei LSS beeinträchtigt ist, was zu Störungen in der segmentalen Verarbeitung und beim Zugriff auf Phoneme führen könnte, oder ob phonologische Defizite vielmehr auf kognitive Vermittlungsdefizite zurückzuführen sind, die den Zugang zu intakten phonologischen Repräsentationen einschränken. Die Dissertation konzentrierte sich auf die italienische Sprache, die eine höhere Transparenz aufweist als das Englische und sich durch andere akustische Merkmale im Bereich des lexikalischen Akzents auszeichnet. Dieser Sprachvergleich bietet die Möglichkeit, die sprachübergreifende Generalisierbarkeit von Befunden zu Defiziten in der lexikalischen Akzentverarbeitung und phonologischen Verarbeitung im Zusammenhang mit LSS zu überprüfen. Darüber hinaus bietet das Italienische den methodischen Vorteil, dass quantitative Merkmale auf segmentaler sowie auf prosodischer Ebene als Hinweise auf phonologische Verarbeitungsprozesse und mögliche Defizite dienen können. Letzteres ermöglicht eine kontrollierte, parallele Untersuchung beider linguistischer Ebenen.

### **Methode:**

Insgesamt nahmen 40 Jugendliche mit LSS und 30 altersentsprechende typisch entwickelte (TD) Jugendliche sowie 28 Kinder mit LSS und 29 TD-Kinder an der Studie teil. Die Untersuchungen gliederten sich in vier Studien, die altersgruppenspezifisch durchgeführt wurden. In Studie 1 haben Jugendliche Phoneme identifiziert. Anhand dieser Aufgabe wurde die implizite akustische Sensitivität für Prominenz bei der Phonemidentifikation untersucht. In Studie 2 führten dieselben Jugendlichen eine sensomotorische Synchronisationsaufgabe durch, bei der sie im Takt mit dem wahrgenommenen Rhythmus gesprochener Sätze klopfen sollten, um ihre Sensitivität für prosodische Betonung im Kontext ganzer Sätze zu erfassen. Kinder absolvierten in Studie 3 eine vereinfachte Version der Aufgabe zur Phonemerkennung, mit der die implizite akustische Sensitivität für Prominenz erfasst werden sollte. In Studie 4 wurde ihre Sensitivität für lexikalischen Akzent mittels einer Wahrnehmungsaufgabe erfasst, in der sie zwischen zwei italienischen Minimalpaaren mit unterschiedlicher Betonung (z. B. *papa* ['papa] "Papst" vs. *papà* [pa'pa] "Papa") entlang eines Kontinuums unterscheiden sollten. Beide Aufgaben wurden ausgewählt, weil die Durchführung wenig metalinguistisches Wissen erfordern. Während der Phonemidentifikation bei Kindern wurde zusätzlich Pupillometrie eingesetzt, um implizit sowohl phonologische als auch kognitive Prozesse zu erfassen. Diese Methode bietet ein objektives Maß für den Online-Zugriff auf sprachliche Repräsentationen und reduziert das Risiko falsch-negativer Ergebnisse. Trotz ihres Potenzials wurde sie bisher selten im Kontext von LSS eingesetzt. Alle Teilnehmenden durchliefen zudem eine kognitive Testung. Komorbide Dyskalkulie wurde aufgrund ihres nicht-sprachlichen Charakters als Einschlusskriterium beibehalten, jedoch in den Analysen kontrolliert.

### **Ergebnisse:**

Die Ergebnisse zeigten signifikante Gruppenunterschiede in der Leistung bei der Phonemerkennung in beiden Kohorten (Studie 1 und 3), die nicht durch fragile Repräsentationen des lexikalischen Akzents erklärt werden konnten. Im Gegensatz dazu schienen Unterschiede in der phonologischen Identifikation zwischen Personen mit LSS und ihren TD-Gleichaltrigen—unabhängig vom Alter—durch kognitive Ressourcen beeinflusst zu werden. Bei TD-Jugendlichen (Studie 1) waren die phonologischen Identifikationsraten höher, wenn die Fähigkeit zum Aufmerksamkeitswechsel stark ausgeprägt war, und niedriger bei geringer Ausprägung. Diese Beziehung war jedoch bei Jugendlichen mit LSS nicht erkennbar, da ihre Leistung unabhängig von dieser Fähigkeit durchgehend niedrig blieb. Darüber hinaus trugen kognitive Ressourcen zu den Gruppenunterschieden in den pupillometrischen Reaktionen während der Ablenkungsverarbeitung in der Phonemerkennungsaufgabe bei Kindern (Studie 3) bei. Studie 2 und 4 bestätigten zudem die Vergleichbarkeit der Repräsentationen lexikalischer Betonung. Beide Jugendlichengruppen zeigten

eine ähnliche Ausrichtung auf starke und schwache Silben in der Synchronisationsaufgabe (Studie 2), und auch die kategorialen Wahrnehmungskurven für den lexikalischen Akzent verliefen bei Kindern (Studie 4) konsistent.

**Fazit:**

Insgesamt bestätigt diese Dissertation, dass phonologische und möglicherweise auch lexikalische Akzentrepräsentationen bei Personen mit LSS bis ins späte Kindes- und Jugendalter intakt bleiben. Allerdings scheint der Zugriff auf diese Repräsentationen beeinträchtigt zu sein, wahrscheinlich aufgrund eines Ungleichgewichts zwischen stark und schwach ausgeprägten kognitiven Ressourcen—eine Interaktion, die weiterer empirischer Untersuchung bedarf.

Anstatt eine umfassende phonologische oder prosodische Beeinträchtigung widerzuspiegeln, scheinen Schwierigkeiten bei LSS eher bestimmte Teilbereiche der phonologischen und prosodischen Kompetenz zu betreffen. Dies untermauert die multikomponentielle Natur dieser Domänen, wobei insbesondere phonologisches Bewusstsein eng mit kognitiven Prozessen verknüpft ist. Trotz ihrer Wechselbeziehung entwickeln sich segmentale und prosodische Fähigkeiten weitgehend unabhängig voneinander und zeigen deutliche sprachspezifische Unterschiede—ein ausgereiftes Niveau wird erst im späten Erwachsenenalter erreicht. Zukünftige Studien sollten daher potenzielle Einflussfaktoren wie Sprachtransparenz, sozioökonomischen Status (SES) und Leseerfahrung systematisch berücksichtigen, um ihr Zusammenspiel bei der phonologischen Verarbeitung in LSS besser zu verstehen.

# Table of Contents

1. INTRODUCTION .....	10
1.1 <i>Developmental Dyslexia: Key Pathways to Phenotypic Variability</i> .....	10
1.2 <i>Phonology and Reading</i> .....	12
1.3 <i>Phonological Deficits in DD</i> .....	14
1.4 <i>Cognitive Underpinnings of Phonological Awareness in DD</i> .....	16
1.5 <i>The Cognitive Mediation Hypothesis</i> .....	18
1.6 <i>Lexical Stress, Phonology, and Reading</i> .....	19
1.7 <i>Lexical Stress Impairments in DD</i> .....	21
1.8 <i>The Lexical Stress Sensitivity Hypothesis</i> .....	22
1.9 <i>Aim and Rationale</i> .....	24
2. LEXICAL STRESS AND PHONOLOGY IN ADOLESCENTS WITH AND WITHOUT DD .....	29
2.1 <i>Experimental Cohort</i> .....	29
2.2 <i>Study 1: Prominence and Phonology in Adolescents: Phoneme Monitoring</i> .....	32
2.2.1 Method .....	35
2.2.1.a Experimental Materials .....	35
2.2.1.b Individual Assessment .....	40
2.2.1.c Experimental Procedure .....	42
2.2.1.d Data Pre-processing and Statistical Analyses .....	42
2.2.2 Results .....	43
2.2.2.a Analysis of d'-sensitivity .....	43
2.2.2.b Analysis of Accuracy .....	44
2.2.2.c Reliability Check .....	46
2.2.3 Discussion .....	46
2.3 <i>Study 2: Acoustic Sensitivity to Lexical Stress in Adolescents</i> .....	50
2.3.1 Method .....	53
2.3.1.a Experimental Materials .....	53
2.3.1.b Experimental Procedure .....	56
2.3.1.c Data Pre-processing and Statistical Analyses .....	57
2.3.2 Results .....	59
2.3.2.a Analysis of SMT and cognitive resources .....	59
2.3.2.b Analysis of the Domain of Synchronization .....	60
2.3.2.c Analysis of SMS likelihood .....	61
2.3.2.d Analysis of SMS accuracy .....	62
2.3.2.e Analysis of SMS variability .....	64
2.3.3 Discussion .....	64
3. LEXICAL STRESS AND PHONOLOGY IN CHILDREN WITH AND WITHOUT DD .....	68
3.1 <i>Experimental Cohort</i> .....	68
3.2 <i>Study 3: Prominence and Phonology in Children: Phoneme Monitoring</i> .....	70
3.2.1 Method .....	72
3.2.1.a Experimental Procedure .....	73
3.2.1.b Individual Assessment .....	74
3.2.1.c Data Pre-processing and Statistical Analyses .....	76
3.2.2 Results .....	81
3.2.2.a Analysis of d'-Sensitivity and Accuracy .....	81
3.2.2.b Analysis of Pupillometry .....	82
3.2.3 Discussion .....	84
3.3 <i>Study 4: Acoustic Sensitivity to Lexical Stress in Children</i> .....	88
3.3.1 Method .....	89
3.3.1.a Experimental Procedure .....	89
3.3.1.b Data Pre-processing and Statistical Analyses .....	91
3.3.2 Results .....	91
3.3.2.a Analysis of Identification Responses .....	91
3.3.2.b Analysis of Reaction Times .....	93
3.3.3 Discussion .....	94
4. GENERAL DISCUSSION .....	98
4.1 <i>Synthesis of Background, Methods, and Results</i> .....	98
4.2 <i>Age-Based Analysis of Phoneme Identification Performance</i> .....	101
4.3 <i>Age-Based Analysis of the ability to process Lexical Stress and Prominence</i> .....	102

*4.4 Beyond Acoustic Sensitivity in DD: Rethinking the Lexical Stress Deficit*.....102  
*4.5 Phonological Deficits in DD: Exploring the Nature of Impaired Cognitive Mediation*.....104  
**5. CONCLUSION** .....108  
**6. REFERENCES** .....112

# 1. Introduction

## 1.1 Developmental Dyslexia: Key Pathways to Phenotypic Variability

Being able to read is essential for success in education, employment, accessing media, and utilizing social services (Levin-Zamir & Bertschi, 2018; Smith-Spark et al., 2023; Tops et al., 2021). The acquisition and development of reading is a highly complex task that requires the involvement of various linguistic, cognitive, and sensory domains and subdomains (Al Dahhan et al., 2016; Ardila et al., 2010; Bryant & Bradley, 1983; Chiappe et al., 2001; Cotton & Crewther, 2009). Developmental Dyslexia (DD) is characterized by persistent difficulties in literacy acquisition and development that cannot be attributed to intellectual disability, inadequate educational and socioeconomic exposure, or peripheral deficits (American Psychiatric Association, 2022; Andresen & Monsrud, 2022; Cornoldi & Tressoldi, 2014; Harrison et al., 2021; Sadusky et al., 2022). It is therefore central to understanding the relationship between spoken and written language, as well as the pivotal domains that sustain this link. Notably, DD diagnosis typically occurs after the first years of schooling, with its prevalence in the population estimated to be between 3% and 10% across languages (Barbiero et al., 2019; Miles, 2004; Wagner et al., 2020).

While a growing body of research supports a neurobiological foundation for DD, its precise etiology remains a topic of debate, especially concerning the pathways that connect its underlying core factors to the observable behavioral manifestations (Potier Watkins et al., 2023; Wolf et al., 2024; Ziegler et al., 2020). This connection is further complicated by the substantial variability in the clinical phenotype of individuals with DD (Giofrè et al., 2019; McArthur et al., 2000; Raghuram et al., 2018; Ramus, Pidgeon, et al., 2003). For example, Ramus et al. (2003) found that 59% of children aged 8–12 with DD exhibited motor coordination difficulties, though not all of them were affected. In addition, Giofrè et al. (2019) analyzed over 300 children with DD and identified two clearly differentiated cognitive profiles across participants—one with a higher average IQ of around 113 and another with a lower average IQ of approximately 94, highlighting variability within the population. Furthermore, McArthur et al. (2000) found that 55% of children with DD had comorbid developmental language disorder, yet a substantial proportion did not exhibit such difficulties. Likewise, Raghuram et al. (2018) reported that while 79% of the 23 children in their cohort with DD exhibited deficits in one or more domains of visual function, the remaining children did not show any such impairments. Overall, these studies indicate that deficits and comorbidities in DD are highly frequent and span linguistic, sensory, and cognitive domains.

Beyond individual differences, the DD phenotype appears to be influenced by both age and language type (Carioti et al., 2021; Danelli et al., 2017; Eloranta et al., 2019; Heim et al., 2008; Landerl et al., 2013; Martin et al., 2016; Menghini et al., 2010; Snowling, 2003; Ziegler et al., 2010). For example, several studies suggest that reading skills and associated deficits are more frequent in children, while a tendency toward compensation emerges in adulthood (Danelli et al., 2017; Eloranta et al., 2019; Heim et al., 2008; Menghini et al., 2010; Snowling, 2003). Notably, this compensatory process seems to be mediated by the degree of transparency and orthographic depth of the environment language (Carioti et al., 2021; Landerl et al., 2013; Martin et al., 2016; Ziegler et al., 2010), which refers to the degree of correspondence between sounds and symbols in a given language (Landerl et al., 2013; Ziegler et al., 2010). Specifically, Carioti et al. (2021) systematically reviewed 113 studies on DD published between 2013 and 2021 and found that reading accuracy tends to become less problematic in adulthood in orthographic systems with a more transparent sound-to-grapheme relationship (Landerl et al., 2013; Ziegler et al., 2010). Furthermore, Martin et al. (2016) confirmed through their meta-analysis the presence of brain abnormalities and compensatory mechanisms that appear to vary between shallow and deep orthographies. For example, in deep orthographies (DO), such as English, dyslexic underactivation in the left inferior frontal gyrus (*pars triangularis*) may reflect greater difficulties with phonological and lexico-semantic processing due to the reliance on whole-word or exception word reading strategies. In contrast, in shallow orthographies (SO), like German or Italian, underactivation was more pronounced in the left frontal operculum and IFG *pars orbitalis*—regions involved in sublexical phonological decoding—suggesting that dyslexic readers in SO may struggle more with accessing phonological output representations. Additionally, overactivation in the left precentral gyrus in SO was interpreted as a compensatory reliance on articulatory strategies, possibly reflecting greater use of covert articulation due to more consistent grapheme–phoneme mappings. In DO, overactivation was observed only in the left anterior insula, which the authors linked to increased cognitive effort and error monitoring during more demanding reading tasks.

Given the intrinsic variability of the clinical phenotype across individuals with DD, several multifactorial models have been proposed as alternatives to single-cause explanations (Lorusso & Toraldo, 2023; Pennington, 2006; Potier Watkins et al., 2023; van Bergen et al., 2014; Ziegler et al., 2020). However, understanding the developmental trajectories and probabilistic interactions of the core deficits in DD remains a central focus of research (Lorusso & Toraldo, 2023; van Bergen et al., 2014; Ziegler et al., 2020). Notably, phonological deficits have been frequently reported in at least 50% of DD samples across studies based on alphabetic languages (Dębska et al., 2022; Ramus, Pidgeon, et al., 2003; Reid et al., 2007; Sprenger-Charolles et al., 2009). This high prevalence has led

also to the proposal of a potential dyslexia subtype characterized by phonological impairments as a core deficit (Potier Watkins et al., 2023). Nevertheless, its underlying etiological factors remain a subject of debate (Ramus, Rosen, et al., 2003; Vandermosten et al., 2010; Virtala et al., 2020; Wolf et al., 2024). The current thesis contributes to this ongoing discussion by examining the interplay between phonological deficits and lexical stress impairments at two distinct stages of development—specifically in children and adolescents with and without DD. By capturing differences between age groups, the findings may help inform and orient future research on the developmental trajectory of these impairments. The thesis focuses on Italian, a language with a shallower orthographic depth compared to English. The fact that most research on DD has centered on English (Sprenger-Charolles et al., 2009) compromises cross-linguistic generalizations (Share, 2008).

## 1.2 Phonology and Reading

The term “phonology” refers to the system of sounds in a language and how they are structured and processed (Wagner & Torgesen, 1987). Phonological abilities encompass a broad set of functions, ranging from basic speech perception, such as sound discrimination, to higher-level metacognitive skills involved in manipulating sounds (Wagner & Torgesen, 1987; Welbourne et al., 2018; Wolf et al., 2024; Ziegler & Goswami, 2005). Infants begin acquiring the speech sounds of their native language early in life, progressively refining their ability to perceive and categorize phonemes through exposure to their linguistic environment (Kuhl, 2010; Werker & Tees, 2005). Research indicates that during the first 6 months of life, infants initially discriminate a wide range of speech sounds, including those not present in their native language. However, as they gain more experience with their language, their perceptual system adapts, enhancing sensitivity to native contrasts while reducing sensitivity to non-native distinctions (Galle & McMurray, 2014; Kuhl et al., 2005). This process, often referred to as perceptual narrowing (Werker & Tees, 2005), enables infants to gradually organize speech sounds into language-specific categories between 6 and 12 months of age (Kuhl, 2010; Kuhl et al., 1992). These language-specific categories are commonly referred to as segmental phonological representations, which are abstract units that encode phonetic and phonemic characteristics (Fowler, 1991), helping infants differentiate speech sounds into distinct phonemes (Sutherland & Gillon, 2007). These representations can be described acoustically, for instance in terms of pitch, loudness, and duration, or articulatory features such as place and manner of articulation (Goswami 2012).

At the most basic level, they involve the ability to recognize and mentally represent individual phonemes that make up words. For example, in the word *banana*, this includes identifying the sequence of sounds /b/, /ə/, /n/, /æ/, /n/, /ə/. Although infants begin forming phonemes by the end of between 6 and 12 months of age, the foundational mastery of phonological representations typically

occurs between 3 and 4 years of age (Goswami, 2012; Goswami, 2019). Well-formed phonological representations are stable, detailed, and distinct mental constructs that support accurate speech perception, storage, and manipulation (van der Lely & Pinker, 2014; Sutherland & Gillon, 2007).

Well-formed phonological representations are a prerequisite for the ability to actively manipulate phonemes. This ability, known as phonological awareness (Treiman & Zukowski, 1991; Werker & Tees, 1987), involves the conscious manipulation of speech sounds and typically emerges later in childhood, around the age of five (Carroll et al., 2003). Although the stages leading to the development of phonological representations and, subsequently, phonological awareness are still debated (Joseph, 2011; Sutherland & Gillon, 2007), they appear to follow a hierarchical progression of competencies (Treiman & Zukowski, 1991), where the acquisition of the representations is necessary for the development of the ability to actively act on them. For example, in the transition from phonological representations to phonological awareness, children may first recognize that *cat* and *hat* rhyme—both ending in the same sound pattern. At a slightly more advanced level, they might notice that *cat* and *cap* share the same initial sound, demonstrating awareness of alliteration. As their skills develop further, they can blend individual sounds to form the word *cat* (/k/ /æ/ /t/). Ultimately, at the highest level of phoneme manipulation, they might be able to replace the initial /k/ in *cat* with /h/ to form *hat*, showing a flexible and conscious control over individual sounds (Joseph, 2011). This means that sound mapping progresses from an initial sensitivity to larger phonological units, such as words and syllables, to the awareness of smaller units like phonemes. This latter stage is further reinforced by literacy acquisition, as full access to phonemes only emerges once children are explicitly taught to read and write.

However, the relationship between phonology and literacy is not unidirectional. While literacy can influence phonology, both basic perceptual phonological representations and phonological awareness play a crucial role in literacy development, as they support the acquisition of phoneme–grapheme correspondence rules (Carroll et al., 2003; Castles & Coltheart, 2004; Ehri, 2005; Milankov et al., 2021; Share, 1995; Ziegler & Goswami, 2005). For example, a child with well-developed phonological representations can accurately distinguish between phonemes like /p/ and /b/, while phonological awareness enables them to understand that "bat" consists of three distinct sounds—/b/, /æ/, and /t/—which correspond to specific letters in its written form. Although mappings underlying those rules develop with some cross-linguistic variations (Siok & Fletcher, 2001; Ziegler & Goswami, 2005), they represent a universal critical step in achieving fluent and accurate reading skills. Conversion rules, overall, enable readers to decode written words, facilitating the transition from print to speech and viceversa.(Carroll et al., 2003; Castles & Coltheart, 2004; Milankov et al., 2021; Siok & Fletcher, 2001; Stanovich, 2017; Ziegler & Goswami, 2005). Notably, neuroimaging studies have

shown connectivity between key brain regions involved in integrating sound and grapheme processing (Price, 2012; Vandermosten et al., 2020).

All the aforementioned studies support the view that phonological and literacy development are closely intertwined, with phonological representations serving as a foundational basis for the emergence and acquisition of reading skills (Carroll et al., 2003; Castles & Coltheart, 2004; Ehri, 2005; Milankov et al., 2021; Share, 1995; Stanovich, 2017; Welbourne et al., 2018). This thesis specifically focuses on the perception of basic phonological representations—namely, phonemes—and examined how they interact with prosody and cognitive resources in shaping literacy outcomes in individuals with DD. In so doing, phonemes are distinguished from the representations of lexical stress. While lexical stress can be regarded as part of phonology (Broś et al., 2021), the two levels are kept distinct in this thesis to better reflect the comprehensive nature of lexical stress and to more clearly examine its interplay with the perceptual processing of phonemes.

### **1.3 Phonological Deficits in DD**

Given the strong connection between phonology and literacy, it is not surprising that multiple perceptual phonological skills, specifically concerning phoneme processing, have frequently been reported as impaired in individuals with DD (Farquharson et al., 2014; Marchetti et al., 2023; Masterson et al., 1995; Noordenbos & Serniclaes, 2015; O'Brien et al., 2020; Snowling, 1995, 2003; Tilanus et al., 2013; Vandermosten et al., 2010; Werker & Tees, 2005). For instance, the ability to discriminate, identify and classify speech sounds into specific categories has been found to be weaker in individuals with DD (Masterson et al., 1995; Noordenbos & Serniclaes, 2015; O'Brien et al., 2020; Thomson & Goswami, 2010; Vandermosten et al., 2010; Virtala et al., 2020; Werker & Tees, 1987). Vandermosten et al. (2010) tested 62 Dutch-speaking adults (31 with DD and 31 typically developing readers, matched for age, gender, and education) in a phonological categorization task. Participants were asked to discriminate between sounds based on either temporal or steady-state acoustic cues. The contrast between /ba/ and /da/ relied on temporal cues, specifically the rapid changes in formant transitions at the onset of the plosive consonants, which differ in timing and direction and unfold within a very brief time window. In contrast, the /u/ vs. /y/ contrast relied on steady-state cues, as vowels are characterized by relatively stable spectral patterns—such as consistent formant frequencies—maintained over a longer duration. Unlike plosives, vowels do not involve abrupt acoustic changes; instead, they differ in sustained articulatory configurations like tongue position and lip rounding, which shape their distinct acoustic signatures over time. Results revealed that individuals with developmental dyslexia (DD) exhibited significant deficits in categorizing sounds defined by temporal cues, such as plosives, supporting the view that rapid auditory processing may be impaired in this population. However, more recent evidence has suggested that even contrasts

involving vowels may pose challenges for individuals with DD when presented within an ecological context (Virtala et al., 2020). In addition to difficulties in distinguishing between phoneme categories, Serniclaes et al. (2004) observed that 18 French-speaking adults with DD also showed a reduced ability to adjust for subtle acoustic variations within the same phoneme category, compared to their typically developing counterparts. This evidence in DD suggests an increased sensitivity to allophonic variations within phoneme categories, coupled with a reduced sensitivity to contrasts between phoneme categories. This pattern appears to contribute to overall altered phonological representations in DD.

Expanding on these findings, Ramus et al. (2013) tested a large cohort of 129 English-speaking children aged 8–12 years, divided into groups with pure developmental language disorder (DLD), pure DD, combined DD and DLD, and controls, and found that only a minority (33%) of children with pure DD exhibited impairments in tasks measuring the integrity of phonological representation abilities, such as discrimination and categorization. In contrast, the vast majority (66%) showed significantly lower performance on tasks assessing phonological awareness and phonological working memory. For example, in the Rhymes and Spoonerisms subtest of the Phonological Assessment Battery (Frederickson et al., 1997), children were asked to complete tasks such as identifying rhyming words (*e.g.*, *hat–cat*) or producing spoonerisms by swapping initial sounds in word pairs (*e.g.*, *saying 'teep cup' for 'keep tup'*). Verbal short-term and working memory were assessed using the forwards and backwards digit span task from the WISC-III (Wechsler, 1992), in which children had to repeat sequences of digits either in the same or reverse order (*e.g.*, hearing 3-7-2 and repeating 2-7-3). However, these studies did not control for music training, which has been suggested to enhance both acoustic sensitivity and phonological representations (Degé & Schwarzer, 2011; Kraus et al., 2014; Tierney & Kraus, 2013). Evidence indicates that individuals with dyslexia who have received extensive music training may perform better on phonological and auditory tasks compared to dyslexic peers without such training (Weiss et al., 2014; Zuk et al., 2018), possibly reflecting compensatory mechanisms (Rathcke & Lin, 2021). Thus, it remains unclear to what extent the relatively low rate of phonological representation deficits reported in some studies may have been moderated by unmeasured variability in participants' musical background.

Nevertheless, these findings of a perceptual predominant phonological awareness deficit align with a number of studies reporting phonological awareness as a consistently deficient domain of phonology in DD (Farquharson et al., 2014; Marchetti et al., 2023; Snowling, 1995, 2003; Tilanus et al., 2013). Notably, in alphabetic languages where the relationship between sounds and letters is more consistent (*i.e.*, where the same sound is usually spelled the same way), children—including those with DD—may find it somewhat easier to develop phonological and literacy skills over time. This

suggests that orthographic consistency can, in some cases, help mitigate the impact of phonological awareness difficulties as children grow older (Ziegler et al., 2010). However, evidence overall indicates that phonological awareness deficits in individuals with DD remain relatively stable, regardless of age or the transparency of the language system (Carioti et al., 2021; Ziegler et al., 2003). In other words, even when a language has regular sound-to-spelling correspondences that support phonological and reading development, children with DD continue to struggle with perceiving and manipulating the sounds within words. For example, a recent study by Schwarz et al. (2024) tested 28 Spanish-speaking adults with and without DD using the PECO test (Ramos & Gordillo, 2007), which includes phonological awareness tasks targeting both expanded representations, such as syllables (e.g., syllable addition: adding *ca* to *sa* to form *casa*, 'house'), and basic representations, such as individual phonemes (e.g., phoneme omission: saying *asa* when omitting the /k/ from *casa*; or phoneme identification: selecting a picture that begins with the /s/ sound, such as *sol*, 'sun'). The results consistently showed that individuals with DD had greater difficulty manipulating both syllabic and phonemic structures compared to typically developing peers.

Therefore, the higher prevalence and growing body of studies highlighting phonological awareness deficits over those examining phonological representations raises the question of whether impaired phonological processing in DD, which predominantly seems to affect conscious access to phonological representations, necessarily entails deficits in the representations themselves.

#### **1.4 Cognitive Underpinnings of Phonological Awareness in DD**

The conscious manipulation of phonemes involved in phonological awareness tasks requires significant cognitive demand (Cardoso et al., 2013; Farrar & Ashwell, 2012; Gathercole et al., 2006; Gathercole & Baddeley, 1995; Ortiz-Mantilla et al., 2010; Ramus & Szenkovits, 2008; Tal & Shaul, 2024; Yoncheva et al., 2014). For example, performing a spoonerism task—which involves swapping the initial sounds of two words—requires the coordination of several cognitive operations. The individual must first engage attentional control, the ability to selectively focus on relevant stimuli (Ebert & Kohnert, 2011; Ortiz-Mantilla et al., 2010; Tonér et al., 2021; Valdois, 2022; Yoncheva et al., 2010), to process both words. Then, they must identify and isolate their initial phonemes (e.g., /d/ from *duna* “dune” and /l/ from *lama* “mud”). These sounds must be held in working memory, the capacity to temporarily store and manipulate information (Baddeley, 2003; Ramus & Szenkovits, 2008), while the rest of the word structure is also retained. Successfully swapping the sounds to produce *luna* “moon” and *dama* “lady” involves inhibitory control, the ability to suppress the automatic tendency to repeat the original forms (Daucourt et al., 2018; Doyle et al., 2018; Wang & Yang, 2015), as well as cognitive flexibility, the capacity to adapt one’s thinking (McNeill et al., 2025; Tal & Shaul, 2024) and shifting attention, as the ability to quickly reconfigure mental

representations in order to reassemble the phonemes into new, meaningful combinations (Daucourt et al., 2018; Gresch et al., 2024; Hari & Renvall, 2001; Luna-Rodriguez et al., 2018; Wager et al., 2006).

In line with these results, Cardoso et al. (2013) analyzed 40 Portuguese-speaking children in their first year of literacy acquisition, finding a correlation between working memory, literacy development, and phonological awareness, assessed through tasks such as phoneme synthesis, segmentation, and rhyme identification. Specifically, children with stronger working memory demonstrated more advanced phonological awareness and progressed further in literacy stages, while those with weaker working memory faced greater challenges in phonological processing and remained in earlier literacy phases. Similarly, Yoncheva et al. (2014) reported that in proficient adult readers, a rhyming task used to assess phonological awareness activated a left-lateralized attention-related brain circuit, particularly in posterior and temporal regions, highlighting its role in phonological processing. Furthermore, Tal and Shaul (2024) assessed cognitive flexibility and emergent literacy in 1,050 Hebrew-speaking kindergarteners and found that poor phoneme awareness by means of initial syllable identification and last phoneme identification correlated with moderate to low cognitive flexibility, emphasizing the central role of executive functions in facilitating conscious access to phonology. Therefore, working memory, attention skills, and executive functions seem to be tightly tied up with phonological awareness manipulations.

Crucially, evidence suggests that these specific cognitive abilities supporting phoneme-level manipulation are often impaired in individuals with DD (Barbosa et al., 2019; Cheng et al., 2021; Chutko et al., 2022; Gathercole et al., 2006; Gathercole & Baddeley, 1995; Knoop-van Campen et al., 2018; Lallier et al., 2010; Masoura et al., 2021; Menghini et al., 2011; Ramus & Szenkovits, 2008; Valdois, 2022). For instance, a substantial body of research has identified reduced working memory capacity in DD (Gathercole et al., 2006; Gathercole & Baddeley, 1995; Knoop-van Campen et al., 2018; Masoura et al., 2021; Menghini et al., 2011). Similarly, studies on DD consistently report the occurrence of attentional and executive functions deficits (Barbosa et al., 2019; Cheng et al., 2021; Chutko et al., 2022; Valdois, 2022).

All in all, a growing body of evidence highlights the close involvement of working memory, attentional control, and executive functions—such as inhibitory control and cognitive flexibility—in tasks requiring conscious phoneme manipulation. Deficits in these cognitive domains have been shown to correlate with poorer phonological awareness and literacy outcomes across both children and adults. These findings suggest a critical inquiry into whether impairments in cognitive capacities may interfere with conscious access to phonology. This question is particularly relevant for

understanding the nature of phonological difficulties in DD, as it raises the possibility that such deficits may also reflect broader cognitive constraints.

### **1.5 The Cognitive Mediation Hypothesis**

An increasing number of studies indicate that specific cognitive deficits, particularly in working memory, attention, and executive functions, may disrupt the precise access to phonemes (Lallier et al., 2010; Ramus & Szenkovits, 2008). For instance, Ramus and Szenkovits (2008) tested French adults with and without DD on various perceptual and productive phonological tasks with increasing cognitive load (Chen et al., 2023) and observed group-level differences only in the more cognitively demanding tasks. Participants were asked to discriminate and reproduce foreign phonological contrasts embedded in nonwords. For example, in the single-item condition, they heard and repeated a single CVCV nonword such as *pika*, while in the sequence condition, they were presented with two or three nonwords in a row, such as *pika-tugu-bada*, and had to discriminate or reproduce the entire sequence. Group-level differences emerged only in the sequence condition, which required retaining and manipulating multiple phonological forms, thereby placing greater demands on working memory. Consequently, Ramus and Szenkovits (2008) interpreted these findings as evidence of an impairment in external computations governing access to phonological representations, primarily working memory, rather than a deficit in the phonological representations themselves. In addition, Lallier et al. (2010) tested 26 English-speaking adults, with and without DD and phonological awareness impairments, using a stream segregation paradigm. Participants listened to auditory or visual sequences with tempo and reported whether they perceived one or two streams. Results showed that individuals with DD required a significantly longer tempo to perceive two successive stimuli as separate streams rather than as a single one, regardless of sensory modality. The analysis of brain responses in the form Event-Related Potential further supported these behavioral results, revealing differences between groups in response to tempo variations. Based on these findings, the authors concluded that individuals with DD and impaired phonological awareness exhibit a reduced ability to rapidly refocus attention across fast stimuli, i.e. phonemes, thus further supporting a connection between deficits in cognitive domains and difficulties in phonological access in individuals with DD.

However, manifestation of cognitive deficits remains highly heterogeneous in DD (Cowan et al., 2017; Lukov et al., 2015; Menghini et al., 2010). For example, Menghini et al. (2010) found that 10 on the 60 Italian children with DD reported executive functions deficits. In addition, while testing attentional abilities in Hebrew participants with DD, Lukov et al. (2015) identified a small subgroup with attention scores within the normal range, in contrast to the remaining participants who did exhibit attention deficits. In this vein, Lewandowska et al. (2014) tested the hypothesis of distinct clusters of attention and executive function deficits in DD. Test scores from 78 Polish children identified distinct

subgroups with specific attentional deficits: one subgroup exhibited impairments in divided attention and cognitive flexibility, another showed deficits primarily in attentional shifting, and a third displayed pronounced difficulties in vigilance. Following the perspective of cognitive heterogeneity in DD, Cowan et al. (2017) investigated the memory profiles of English-speaking adolescents with and without DD, focusing on two components: phonological working memory and serial order memory. Phonological working memory was assessed using a nonword repetition task, where participants repeated sequences such as *mav* or *sopitlak*. To examine serial order memory, defined as the ability to recall items in the correct sequence, they compared performance when both the items and their order had to be correct (strict scoring) versus when only the correct items were counted, regardless of order (lax scoring). For example, repeating the sequence *dap–lin–vok* in the correct order scored higher than recalling the same items in a different order. While group differences in phonological memory disappeared when controlling for IQ, differences in serial order memory persisted, suggesting a specific weakness in maintaining the correct sequence of information in individuals with DD.

Overall, these studies suggest that the cognitive heterogeneity in DD extends beyond the mere presence or absence of specific deficits to variations in the nature of impairments across domains as well as in their interactions with IQ. Given the evidence linking distinct cognitive abilities to conscious access to phonemes in both typical and atypical populations, the hypothesis that individual cognitive resources, whether intact or impaired, may simultaneously or interactively contribute to phonological awareness difficulties in individuals with DD cannot be ruled out. Such variability likely reflects individual differences in cognitive profiles across domains such as attention, working memory, and executive functions.

## **1.6 Lexical Stress, Phonology, and Reading**

Beyond cognitive processes, lexical stress also appears to play a crucial role in the development of basic phonological representations such as phonemes (Bernard & Gervain, 2012; Cumming, Wilson, & Goswami, 2015; Demuth, 2015; Esteve-Gibert & Prieto, 2013; Fernald, 1989; Frazier et al., 2006; Grosjean & Gee, 1987; Hallé et al., 1991; James, 1988; Leong et al., 2014; Lleo & Demuth, 1999; Mampe et al., 2009; Ramus & Ahissar, 2012; Singh et al., 2002; Snow & Balog, 2002; Zhang & Zhang, 2019). Lexical stress is a prosodic property of syllables, but its exact nature remains subject to ongoing debate (Andrikopoulou et al., 2021). Phonologically, it is often regarded as part of hierarchically organized phonological representations (Broś et al., 2021). In this view, lexical stress may be fully specified in the lexicon as a component of lexical representation (Broś et al., 2021), making it distinct from the concept of prominence (Ladd & Arvaniti, 2023). Prominence refers to an

acoustic feature that enables a linguistic unit to stand out from the surrounding elements in speech (Baumann & Winter, 2018). Phonetically, stress is associated with multiple acoustic cues (Mousikou et al., 2024; Quam & Swingley, 2014; Williams & Wood, 2012), whose variations enhance the unit's salience (Baroni, 2014; MacLeod, 2015; Williams & Wood, 2012), thereby contributing to its prominence (Baumann & Winter, 2018). Notably, lexical stress patterns can contribute to what is known as speech rhythm (Leong, 2013; Poeppel & Assaneo, 2020; Rathcke & Smith, 2015), which, phonetically, can be described as the amplitude modulations of the speech signal (Leong, 2013; Poeppel & Assaneo, 2020; Rathcke & Smith, 2015). In this thesis, within the context of Italian as the experimental language, we assume lexical stress to be part of the lexicon, characterized by prominence and increased acoustic salience (Eriksson, Suni, Vainio, & Šimko, 2018). Outside the lexical context, we refer to prominence.

Prominence patterns associated with lexical stress provide a crucial input for the acquisition and development of phonemes. (Bernard & Gervain, 2012; Cumming, Wilson, & Goswami, 2015; Demuth, 2015 ; Esteve-Gibert & Prieto, 2013; Fernald, 1989; Frazier et al., 2006; Grosjean & Gee, 1987; Hallé et al., 1991; James, 1988; Leong et al., 2014; Lleo & Demuth, 1999; Mampe et al., 2009; Ramus & Ahissar, 2012; Singh et al., 2002; Snow & Balog, 2002; Zhang & Zhang, 2019). The ability to perceive lexical stress develops early in life (Cabrera & Gervain, 2020; Corriveau & Goswami, 2009; Corriveau et al., 2007; Fisher & Tokura, 1996; Gervain & Werker, 2013; Goswami, Fosker, Huss, Mead, & Szucs, 2011; Huang et al., 2012; Jusczyk et al., 1992; Piazza et al., 2017; Sato et al., 2012). Typically, infants as young as 6-9 months of age are able to distinguish lexical stress patterns in connected speech (Abboub et al., 2016). Before the end of their first year, infants can reliably use prosodic cues—such as intensity, pitch, and duration—that mark lexical stress salience to parse and group speech, a process known as perceptual precategorization (Fisher & Tokura, 1996; Gervain & Werker, 2013; Hirsh-Pasek et al., 1987; Jusczyk et al., 1992). This process facilitates the extraction of early phonetic and phonological information, supporting the acquisition of initial basic phonological units and the subsequent ability to effectively manipulate them (Bernard & Gervain, 2012; Gervain & Werker, 2013; Gervain et al., 2008; Jusczyk et al., 1992).

Lexical stress contrastivity continues to develop throughout childhood, with sensitivity to the acoustic cues that mark its salience evolving progressively and reaching an adult-like state only well after initial exposure to literacy (Arciuli & Ballard, 2017; Quam & Swingley, 2014). Notably, in the early stages of reading and writing, lexical stress serves as a structural cue that facilitates the perception and proper grouping of syllables into words and words into sentences (Cutler & Butterfield, 1992; Gout et al., 2004; Mattys & Samuel, 1997; Matzinger et al., 2021). Therefore, it is plausible that difficulties in processing lexical stress may negatively affect early segmental

representations as well as reading skills (Bedoin et al., 2016; Colling et al., 2017; Corriveau & Goswami, 2009; Corriveau et al., 2007; Cumming, Wilson, Leong, et al., 2015; Goswami et al., 2016; Goswami, Fosker, Huss, Mead, & Szucs, 2011; Leong & Goswami, 2015; Richards & Goswami, 2015, 2019; Tomas et al., 2017; Tomas & Smith-Lock, 2015).

### 1.7 Lexical Stress Impairments in DD

The hypothesis of a lexical stress impairment in DD has found empirical support in the literature, with several studies highlighting deficits in lexical stress perception and processing among individuals with DD (Caccia & Lorusso, 2020; Caccia et al., 2019; Goswami, Huss, et al., 2013; Goswami, Mead, et al., 2013; Kitzen, 2001; Leong & Goswami, 2013; Leong et al., 2011; Pasquini et al., 2007; Tierney & Kraus, 2013). For instance, Kitzen (2001) found that participants with DD showed significant difficulties distinguishing words based on stress patterns in a picture selection task, indicating deficits in stress perception. Similarly, Leong et al. (2011) examined the ability of 40 English-speaking adults, with and without DD, to perceive syllable stress patterns and discriminate acoustic cues. Participants completed tasks assessing their ability to judge whether word pairs had the same or different stress patterns. Results indicated that individuals with DD exhibited greater difficulty in these tasks compared to the control group, with performance significantly correlated to their sensitivity to rise time—the variation in local amplitude between syllable onset and peak (Pasquini et al., 2007). For example, the syllable *ba* has a shorter rise time because the voicing begins almost immediately, whereas *pa* has a longer rise time due to the aspirated burst of air that delays the onset of voicing. Sensitivity to this acoustic cue is important for distinguishing subtle timing-based contrasts in speech. Subsequently, Goswami et al. (2013) replicated the same paradigm with English children and early adolescents. To assess younger participants, the authors employed a DEEdee task, in which participants matched words, mainly famous names (e.g., cartoon characters), to counterparts where each original syllable was replaced by "DEE" while maintaining the original stress pattern. For example, *Lion King* became *DEEdeeDEE*. Significant difficulties were observed in both clinical cohorts, children and adolescents, with performance strongly linked to their ability to perceive rise time. Therefore, overall, these studies suggest that the perceptual ability to process lexical stress is impaired in individuals with DD due to reduced acoustic sensitivity to the underlying cues.

In addition to lexical stress, a similar pattern has been identified for prominence, the perceived salience of a linguistic unit outside the lexical context, marked by acoustic cues that make it stand out from its surrounding elements (Ladd & Arvaniti, 2023). Caccia et al. (2019) examined the performance of 18 typically developing (TD) children and 15 children with DD, all native Italian speakers, a language with relatively shallow orthography (De Simone et al., 2024; Ziegler & Goswami, 2005), to assess their sensitivity to acoustically salient syllables. Participants listened to

trisyllabic non-words (e.g., /dididi/, /gugugu/, /tatata/) that were systematically manipulated so that one syllable differed from the others in either duration, intensity, or pitch. For example, in a /tatata/ trial, the second syllable might be longer or louder than the first and third. While hearing the stimulus, participants saw a visual representation of the non-word (e.g., TATATA) on screen and were asked to identify which syllable sounded most prominent by pressing one of three keys corresponding to the first, second, or third syllable. The results revealed significantly lower accuracy levels in DD participants compared to the other groups. Furthermore, a study by Caccia and Lorusso (2020) found that children with DD exhibited slower reaction times, particularly when matching musical sequences to corresponding non-words. For example, participants heard a trisyllabic non-word such as *tatáta* (with stress on the second syllable) and were then presented with two musical sequences—each mirroring a different stress pattern—and asked to choose the one that matched the prosody of the spoken stimulus by pressing '1' or '2' on the keyboard. This suggests that DD may also affect speech rhythm processing.

Overall, these studies indicate that lexical stress impairments in DD may result from both a reduced ability to process prominence—likely due to decreased sensitivity to acoustic salience—and broader deficits extending to speech rhythm processing.

### **1.8 The Lexical Stress Sensitivity Hypothesis**

Building on the frequently reported impairments in lexical stress processing in individuals with DD (Caccia & Lorusso, 2020; Caccia et al., 2019; Goswami, Huss, et al., 2013; Goswami, Mead, et al., 2013; Kitzen, 2001; Leong & Goswami, 2013; Leong et al., 2011; Pasquini et al., 2007) and considering its critical role in phonological and literacy development (Bernard & Gervain, 2012; Cumming, Wilson, & Goswami, 2015; Demuth, 2015; Esteve-Gibert & Prieto, 2013; Fernald, 1989; Frazier et al., 2006; Grosjean & Gee, 1987; Hallé et al., 1991; James, 1988; Leong et al., 2014; Lleo & Demuth, 1999; Mampe et al., 2009; Ramus & Ahissar, 2012; Singh et al., 2002; Snow & Balog, 2002; Tomas & Smith-Lock, 2015; Zhang & Zhang, 2019), lexical stress impairment has been proposed as an alternative etiological factor underlying phonological deficits in DD (Goswami, 2019). Rather than attributing these difficulties to deficits in cognitive computations related to phonological awareness, this perspective suggests that challenges in accessing phonological representations stem from impairments in the representations themselves. Specifically, these deficits may result from reduced sensitivity to lexical stress (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013).

The hypothesis of a lexical stress impairment underlying the phonological deficit was first introduced within the framework of the Temporal Sampling Theory (Goswami, 2011). This is a

single-deficit account of developmental dyslexia (DD), meaning that—as introduced in Section 1.1—it attributes the clinical condition to a single underlying impairment rather than multiple contributing factors. Within this framework, DD is specifically proposed to arise from a misalignment between the rise times of syllabic speech amplitude and delta neural oscillations (0.5–3 Hz) (Goswami, 2011; Keshavarzi et al., 2022), which are responsible for encoding them (Gunasekaran et al., 2023; Poeppel, 2014). This altered mechanism disrupts the accurate encoding of the alternation between stressed and unstressed syllables, thereby hindering the extraction of auditory information at the syllabic level, including phonetic information crucial for phonological processing (Goswami, 2011; Goswami, 2019; Keshavarzi et al., 2022). For example, considering again the syllables *pa* and *ba*—one with a longer and the other with a shorter rise time—individuals with DD may have difficulty tracking this difference and accurately matching the acoustic cues to delta-band neural oscillations. This mismatch can lead to imprecise encoding of syllable structure, making it harder to distinguish phonemes such as /b/ and /d/. More into details, several studies (Goswami, Mead, et al., 2013; Leong et al., 2011; Pasquini et al., 2007) have found major difficulties in individuals with DD in processing longer rise times as acoustic correlate underlying lexical stress, particularly affecting stressed and therefore most prominent syllables.

However, the evidence surrounding Temporal Sampling Theory is mixed (Anastasiou & Protopapas, 2014; Barry et al., 2012; Mundy & Carroll, 2013). For instance, Barry et al. (2012) analyzed the performance of 14 German-speaking adults with dyslexia compared to control participants matched for age and gender on two lexical stress processing tasks. In the first task, participants were asked to indicate the correct location of stress in existing verbs. In the second task, they made agreement judgments regarding minimal pair verb agreement, where the verb pairs differed based on stress location. Although group-level differences between TD and DD were observed across both tasks, the authors attributed these differences to response pattern biases rather than genuine deficits in stress processing based on acoustic cues. For example, the DD group could not reliably locate stress on the stem but could correctly process it when already applied. This interpretation was further supported by the fact that the acoustic cues underlying lexical stress in the verbs were exaggerated to enhance their salience. Accordingly, Anastasiou and Protopapas (2014) failed to find group-level differences in lexical stress processing among 29 Greek adolescents with and without dyslexia, matched for age and gender, in a task requiring participants to locate stress in strings composed of three repetitions of the same syllable. However, a significant disparity was observed when participants were tasked with correctly placing stress diacritics. The authors interpreted these findings as supportive of the idea that lexical stress deficits in individuals with dyslexia are more likely linked to higher levels of stress awareness and cognitive overload, rather than deficient per se.

Similarly, Rathcke and Lin (2021) compared the performance of English-speaking adults with and without DD in identifying phoneme targets embedded in syllables with varying acoustic prominence. They found that identification rates were comparable for highly prominent syllables but significantly lower for less prominent ones. As this effect was not directly linked to acoustic saliency, the authors argued that it could be attributed to potential compensatory mechanisms related to working memory deficits. To this point, it is worth noting that adults with higher levels of music training showed improved synchronization to metrically weak syllables, suggesting that musical expertise may provide compensatory support in contexts where phonological or memory resources are taxed (Rathcke & Lin, 2021). Notably, a recent meta-analysis conducted by Mundy and Wood (2024) on speech prosodic processing in individuals with DD, synthesizing 124 effect sizes from 37 studies with data from 1,771 participants (mean age = 13.7 years, range: 6–26) across various languages, found evidence supporting a moderate-to-large prosodic impairment. However, this impairment was specifically associated with tasks requiring reflection on and processing of speech prosody (referred by the authors as prosodic competence cf. Wade-Woolley et al. 2022 p.166), particularly in metacognitive tasks that demand prosodic awareness and cognitive skills. Notably, evidence supporting inadequate lexical stress representations has been reported as less consistent, particularly in languages with more transparent orthographies, such as Italian (Wade-Woolley et al., 2022).

Taken together, the studies reviewed above present a mixed picture: while several report difficulties in lexical stress processing among individuals with DD, others suggest that these differences may stem from task demands or metalinguistic awareness, rather than from a core perceptual deficit. Therefore, this mixed picture leaves open critical questions regarding whether lexical stress representations are inherently impaired in individuals with DD, as predicted by the Temporal Sampling Framework, or if the deficit lies in external, possibly cognitive computations, restricting access to segmental and possibly also prosodic levels. Furthermore, it remains uncertain whether this condition varies depending on the orthographic depth of a language or across different age groups, given that lexical stress sensitivity continues to develop and change throughout childhood and adolescence until it reaches a stable state in adulthood.

## **1.9 Aim and Rationale**

Despite extensive research, several questions remain unresolved regarding the nature and developmental trajectories of phonological and lexical stress representations in individuals with DD, including how these representations interact with each other—whether causally or not—and how they relate to the ability to consciously access them. To clarify the interplay between the perception of lexical stress and that of phonemes, the present thesis investigates acoustic sensitivity to prosodically marked prominent syllables and acoustic salience—both considered key features of lexical stress

sensitivity (Eriksson et al., 2018; Gussenhoven; Levis & Silpachai, 2018)—and their association with basic segmental phonological representations and awareness in Italian-speaking children and adolescents. By exploring these interplays at two key developmental stages—childhood and adolescence—the thesis accounts for the possibility that some compensatory mechanisms may emerge over time, potentially altering at least in part how phonological and prosodic deficits present in DD group.

Furthermore, the current thesis examines the mediating role of individual cognitive profiles, conceptualized here as the interactive effects of different cognitive resources (whether intact or impaired), across both lexical stress and phonological abilities. In doing so, it aims to clarify whether phonological difficulties in DD stem from impaired acoustic sensitivity to lexical stress—potentially affecting the integrity of segmental representations—or whether they instead reflect limitations in computations, primarily cognitive processes, that restrict access to otherwise intact phonological and lexical stress representations. Given that musical training has been suggested to enhance phonological processing and may therefore act as a potential confounder, participants' levels of music training were also assessed and considered in the present research (Degé & Schwarzer, 2011; Kraus et al., 2014; Tierney & Kraus, 2013; Weiss et al., 2014; Zuk et al., 2018).

This thesis addresses the following guiding questions:

- Whether lexical stress representations are inherently impaired in individuals with DD, thereby disrupting the formation of phonological representations and, consequently, hindering access to them.
- Whether there are developmental differences between late childhood and adolescence in the relationship between lexical stress and phonological representations.
- To what extent cognitive heterogeneity in DD influences the development of phonology and lexical stress—specifically, whether observed impairments reflect deficits in the representations themselves, or rather stem from external, possibly cognitive, computations that restrict access to otherwise intact segmental and prosodic structures.

The language employed in the current thesis is Italian which has a phonological inventory of seven vowels and 23 consonantal phonemes (Zanobini et al., 2011) and follows a largely consistent one-to-one phoneme-to-grapheme correspondence, with only minor exceptions (Angelelli et al., 2016). In a few cases, consonantal spellings vary depending on the following sound, such as the phoneme /k/, which is represented as 'C' in *cubo* ('cube') but as 'CH' in *chela* ('claw'). Additionally, phoneme-to-orthography conventions apply in specific instances, such as the /kw/ sound, which may be transcribed as 'Q,' 'CQ,' or 'QQ,' depending on lexical and morphological factors (Angelelli et al.,

2016). However, these exceptions are relatively limited<sup>1</sup>, and the relationship between phonology and orthography in Italian is overall consistently sustained. A clear example is the treatment of geminate consonants, which are reliably represented in spelling (e.g., *pala* 'shovel' vs. *palla* 'ball'), reflecting the phonemic status of consonant length in the language. Therefore, Italian has a significantly lower orthographic depth compared to English, where the relationships between orthography and phonology are less consistent and require greater exposure for acquisition (Seymour et al., 2003; Ziegler et al., 2010).

Some degree of consistency in Italian can also be observed at the prosodic level, particularly in lexical stress (D'Imperio & Rosenthal, 1999). Although lexical stress in Italian is not predictable, it follows a predominant pattern, with stress most commonly falling on the penultimate syllable (D'Imperio & Rosenthal, 1999). Specifically, trisyllabic words that follow a weak-strong stress pattern—where a less prominent syllable precedes a more prominent one (e.g., *ma'tita*)—are dominant in Italian, whereas trisyllabic words with a strong-weak pattern (e.g., *'gomito*), characterized by antepenultimate stress, are less frequent. Exceptions include words with antepenultimate and final stress. The latter is the only stress pattern to be orthographically marked with a diacritic (e.g., *città*, *però*). Moreover, lexical stress in Italian is contrastive, as shown by minimal pairs such as *àncora* [ˈaŋkora] “anchor” vs. *ancóra* [aŋˈkɔra] “again”, or *papa* [ˈpapa] “pope” vs. *papà* [paˈpa] “dad” (Cornoldi et al., 2012; D'Imperio & Rosenthal, 1999).

Traditionally, duration has been considered the primary acoustic correlate of lexical stress perception (Bertinetto, 1980; D'Imperio & Rosenthal, 1999; Ferrero, 1972). This prominence of duration in prosodic marking is consistent with its phonemic role at the segmental level, as seen in contrasts like *pala* “shovel” vs. *palla* “ball” where consonant length changes meaning. However, recent evidence suggests that pitch also plays a primary role in enhancing the acoustic salience of stressed syllables for listeners (Caccia et al., 2019). Although the specific acoustic cues influencing the perception of Italian lexical stress remain a topic of debate, they appear to differ from those of English, which has been the primary focus of research in the DD literature (Share, 2008; Sprenger-Charolles et al., 2009).

The choice of a transparent language like Italian is motivated by the fact that findings on lexical stress impairments in individuals with DD remain inconsistent across languages with lower orthographic depth, along with the relatively limited number of studies conducted in Italian compared to English (Mundy & Wood, 2024). These inconsistencies may be further influenced by the greater

---

<sup>1</sup> Exceptions include: digraphs and trigraphs such as *gli* [ʎ], *gn* [ɲ], *ch/gh* for hard [k]/[g] before front vowels, *ci/gi* for soft [tʃ]/[dʒ], and *sc* before front vowels for [ʃ]. Other irregularities involve the use of silent “h” (e.g., *ha* vs. *a*), context-sensitive voicing of “s” and “z,” and stress marking, which is typically absent except on oxytones or to disambiguate homographs (e.g., *àncora* 'anchor' vs. *ancóra*).

potential for compensation mechanisms in transparent orthographies (Ziegler et al., 2010). The present study aims to bridge this cross-linguistic gap by deepening our understanding of lexical stress processing in Italian. By focusing on a prototypical transparent language, the study contributes to clarifying the role of orthographic transparency in shaping both the nature and detectability of stress-related deficits in DD—thus addressing a fourth overarching research question concerning the influence of language transparency on the manifestation of prosodic and phonological difficulties in DD.

The current thesis tested the following hypotheses:

1. The Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), which posited that regardless of orthographic depth, individuals with DD would exhibit deficits in perceiving lexical stress, reflected in reduced sensitivity to syllabic prominence in nonwords and weakened detection of acoustic salience underlying lexical stress in words and sentences. These deficits were expected to mediate group-level differences in phonological processing—both in phonological representations and awareness—from childhood through adolescence. However, it is expected that the influence of these deficits would diminish in adolescence due to improvements in lexical stress sensitivity.

2. The Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008) which posited that group differences in phonological processing could instead be mediated by individual cognitive factors rather than by reduced sensitivity to lexical stress, with phonological representations remaining intact but access to them being primarily affected.

To test both hypotheses concerning phonological processing in DD, this thesis comprises four empirical studies: the first two involving clinical and typically developing adolescents (Chapter 2), and the latter two involving children with and without DD (Chapter 3). Across both age groups, the main objective was to examine how acoustic sensitivity to syllabic prominence and lexical stress contributes to phoneme identification, and how this relationship may be modulated by individual cognitive profiles.

Studies 1 (Section 2.2) and 3 (Section 3.2) employed a Phoneme Monitoring Task which required participants to identify target phonemes, assessing both the integrity and accessibility of phonological representations (Foss & Swinney, 1973; Wade-Woolley et al., 2022). Using brief trials of recorded nonwords (e.g., [segora'minu], [bipoza'viba]), this method minimized cognitive load while offering an ecologically valid measure of stress perception without requiring explicit linguistic processing. Unlike metalinguistic tasks, phonemes were embedded in syllables with varying

prominence, allowing for a natural and implicit evaluation of lexical stress representations. In addition, only in Study 3 was pupillometry recorded in children as an implicit, real-time measure of the simultaneous processing of both phonemes and cognitive skills.

Studies 2 (Section 2.3) and 4 (Section 3.3) focused on lexical stress perception in linguistic context. Adolescents in Study 2 completed a Sensorimotor Synchronization Task, tapping to the perceived beat of spoken sentences to assess alignment with stress patterns. In contrast, children in Study 4 performed a Perceptual Identification Task, judging which of two minimal pairs best matched a target varying along a lexical stress continuum. In both tasks, complexity was tailored to the developmental level of the participants, and tasks were chosen to minimize metalinguistic demands. Part of the four studies presented in this thesis has been submitted for publication as four distinct journal articles.

Finally, Chapter 4 provides a general discussion of general discussion of the findings emerging from the four studies, while Chapter 5 presents the overall conclusions. This discussion integrates and compares findings from both cohorts, respectively children and adolescents, explores developmental trajectories, and assesses the role of lexical stress sensitivity in phonological processing in DD. Additionally, it examines the broader theoretical and clinical implications of the results. This structured approach is intended to lead the reader through the research progression—from the formulation of broad and specific hypotheses to empirical investigation and, ultimately, a comprehensive synthesis of the findings. In accordance with the structure of this dissertation, which comprises four distinct studies, figures are numbered independently within each study, with numbering restarting from Figure 1. This convention has been adopted to facilitate readability.

## **2. Lexical stress and Phonology in Adolescents with and without DD**

Reading deficits in DD tend to decrease and evolve throughout adulthood (Eloranta et al., 2019; Snowling, 2003; Ziegler & Goswami, 2005). Therefore, it cannot be ruled out that these developmental changes may reflect modifications in their etiological factors (Lorusso & Toraldo, 2023; Pennington, 2006; Potier Watkins et al., 2023; van Bergen et al., 2014; Ziegler et al., 2020). The present two studies contribute to the current thesis by examining the interplay between phonological and lexical stress deficits, along with skills essential for phonology, in adolescents with and without DD. The results will then be compared with data from a child cohort to provide further meaningful insights into the developmental pathways underlying these factors while contributing to the broader research questions.

### **2.1 Experimental Cohort**

Seventy adolescent volunteers were recruited at a local high school in the Greater Milan area. Forty adolescents (29 females) had a formal diagnosis of DD that fulfilled the criteria of the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (American Psychiatric Association, 2022). Twenty-four out of the forty DD participants had comorbid dyscalculia alongside DD. Dyscalculia is a learning disorder that affects the acquisition of numerical and arithmetic processing (Harrison et al., 2021). It is also one of the most common comorbidities of DD, with approximately 40% of individuals with DD experiencing difficulties in arithmetic processing (Wilson et al., 2015). Dyscalculia was retained in the inclusion criteria due to its non-linguistic nature and evidence suggesting that individuals with and without DD share a similar linguistic profile (Vellutino et al., 2004). However, as this co-occurrence may contribute to a more severe cognitive profile (Jordan, 2007), we initially established two distinct clinical groups to enable preliminary comparisons in phonological performance. The clinical sample could thus be segregated into two distinct groups, participants with mixed dyslexia (MD, 19 females) and pure dyslexia (PD, 10 females). Thirty typically developing adolescents (TD, 23 females) took part as a control group.

None of the control participants ever had a developmental record of speech and language difficulties or a related diagnosis, and none experienced specific difficulties with linguistic school subjects (such as foreign language classes, cf. Bazen et al., 2023; Jarsve & Tzagari, 2022; Qianyu, 2022), which was confirmed in private conversations with school teachers. Attention was paid to (proportionally) matching age and gender between the clinical and control groups. Descriptive statistics of age, average school grades, and foreign language grades are compiled in Table 1.

A series of multiple-group comparisons through Kruskal-Wallis (KW) test (Hazra & Gogtay, 2016) for small, unbalanced and non-normal distribution established that there were no significant group-level differences in age ( $H(70) = 0.75, p = .68$ ) and average school grades ( $H(70) = 4.32, p = .115$ ). Gender ratios ( $M_{TD} = .26; M_{PD} = .60; M_{MD} = .30$ ) also did not significantly vary between the three experimental groups ( $H(2) = .2, p = .36$ ). As shown in Table 1, foreign language grades for TD participants were consistently higher, resulting in a significant difference compared to MD participants ( $Z = 3.70, p < .001$ ). Although not reaching statistical significance, the grades still differed from PD participants ( $Z = 1.08, p = .277$ ). All participants were Italian monolinguals without hearing impairments or any psychological (e.g., anxiety, depression), cognitive, or developmental comorbidities (e.g., dyspraxia, ADHD, speech and language delay or impairments).

<b>Group</b>	<b><i>Mdn</i></b>	<b><i>M</i></b>	<b>Min</b>	<b>Max</b>
Age				
TD	16	16.6	14	21
PD	16	16.2	14	18
MD	16	16.2	14	20
Average School Grade (all subjects)				
TD	7	7.4	6	9
PD	7.5	7.3	6	8
MD	7	6.9	5	8
Average Foreign Language Grade				
TD	7	7.5	4	10
PD	6	6.4	4	9
MD	6	6.2	4	7

**Table 1.** <sup>2</sup>Overview of participant demographics comparing the experimental groups (typical development TD, pure dyslexia PD, mixed dyslexia MD) of the present study.

Participants were tested individually in a quiet room located at their respective schools. A testing session lasted approximately one hour in total. Breaks were taken whenever required. Consent

<sup>2</sup> Figures and Tables are numbered independently within each study, restarting from Figure 1.

forms were collected prior to testing. Each experimental session started with a questionnaire that asked participants about their music training, knowledge of other languages, and their grades. Upon completion of the questionnaire, participants engaged with the Phoneme Monitoring Task followed by the Sensorimotor Synchronization with Sentences task along with a series of finger-tapping tasks that are not considered in the current research. The session included cognitive tests in between those tasks.

All participants and their guardians gave informed consent to their participation in the study. The study received ethical approval from the Ethics Board of the University of Konstanz (IRB statement 05/2021).

## **2.2 Study 1: Prominence and Phonology in Adolescents: Phoneme Monitoring**

The lack of integrity in phonological representations in DD has been extensively linked to difficulties in the perceptual categorization of specific phonemes (Noordenbos & Serniclaes, 2015; Serniclaes et al., 2001; Vandermosten et al., 2010; Werker & Tees, 1987) such as the ones which differ in phonological voicing (Bogliotti et al., 2008; Chiappe et al., 2001; Masterson et al., 1995; Zoubrinetzky et al., 2016) or in the place of articulation (Vandermosten et al., 2010). For instance, Masterson et al. (1995) investigated the ability of monolingual English adults with DD to perceive the phonemic contrast between /pa/ and /ba/ based on the primary acoustic cue for phonological voicing (voice-onset time, VOT), and found that they had a weaker ability compared to the typically developing (TD) control group. Acoustic continua consisting of speech stimuli with incrementally manipulated VOT, the time interval between the stop release and the onset voicing (Lisker & Abramson, 1967), have been widely used to study categorical perception of timing cues to phonological contrasts among different groups of listeners, including individuals with DD (Bogliotti et al., 2008; Masterson et al., 1995; Zoubrinetzky et al., 2016). Similarly, acoustic continua with manipulated F2-transitions spanning two places of articulation have been used to study the role of the perception of spectral cues in DD (Vandermosten et al., 2010). Especially obstruent phonemes varying in voicing and place of articulation seem to be challenging for listeners with DD to both identify and discriminate between (Berent et al., 2012; Maassen et al., 2001; Werker & Tees, 1987). For example, Werker and Tees (1987) administered a discrimination task to a group of 14 English children diagnosed with DD. The task involved listening to pairs of syllables from an eight-step formant-transition continuum spanning /ba/ to /da/. The pairings of the stimuli varied from acoustically identical to maximally different (i.e., representing the two ends of the continuum). The results of the study showed that DD had a reduced discrimination ability compared to TD controls. Similarly, Berent et al. (2012) conducted an ABX-discrimination task in which participants were presented with two syllables A and B followed by a third stimulus X that was identical to either A or B. The participants' task was to indicate as quickly as possible whether X was the same stimulus as A or B whereby A and B were taken from a 10-step VOT-continuum between /da/ and /ta/. The responses of 24 Hebrew adults with DD were compared with a TD control group, and the findings revealed that voicing discrimination abilities were significantly lower in the clinical group.

However, not all phonological categories are difficult for listeners with DD to identify and discriminate between. Vandermosten et al. (2010) found that Dutch participants with DD could correctly categorize /u/ vs. /y/ when presented with an acoustic continuum. Vowels like /u/ and /y/ are encoded by acoustic cues based on spectral properties, with F2 being crucial for distinguishing between /u/ and /y/ (Vandermosten et al., 2010). In contrast, differences in voicing and the place of

articulation of oral stops are carried by acoustic cues based primarily on temporal properties of sounds (Masterson et al., 1995; Vandermosten et al., 2010). That is, the voicing contrast is determined by the temporal difference in VOT (Masterson et al., 1995) while the contrast in the place of articulation of oral stops is encoded by the temporal dynamics of the second formant frequency (Vandermosten et al., 2010) and possibly VOT (Yu et al., 2014). As a result, it is plausible that individuals with DD have a specific difficulty with processing phonological contrasts that are encoded by temporal cues (Vandermosten et al., 2010). Timing-based contrasts are prevalent primarily among obstruents but rarely among sonorant consonants (Lisker, 1977). This implies that listeners with DD may have a greater difficulty with obstruent compared to sonorant phonemes while a high level of perceptual sensitivity to frequency-based contrasts has been described as a perceptual advantage of listeners with DD (Abrams et al., 2009; Goswami, Fosker, Huss, Mead, & Szűcs, 2011). However, Virtala et al. (2020) who used an oddball paradigm, a passive listening task in which participants are presented with a series of repetitive standard stimuli interspersed with infrequent deviant stimuli, and demonstrated that difficulties with sound categorization in DD are mainly driven by the acoustic variability of phoneme realization typical of natural speech. The results of the study cast doubt on the assumption that dyslexic difficulties are restricted to temporal cues rather than spectral or melodic ones.

Notably, within the temporal sampling framework (Goswami, 2011), impaired phonological representations are attributed to inadequate lexical stress representations due to reduced acoustic sensitivity in processing rise time. This theoretical explanation was recently tested using a paradigm based on natural speech, involving sensorimotor synchronization with English spoken sentences (Rathcke & Lin, 2021). No evidence was found in support of an acoustic processing impairment related to amplitude rise-time in connected speech (as opposed to isolated words studied previously, see Leong et al. (2011)). Additionally, no notable differences were observed between TD and DD adults in synchronization with strong syllables, whereas a reduced likelihood of synchronization with weak syllables was reported for the clinical group, hypothesized to result from reduced working memory capacity (Rathcke & Lin, 2021). This is particularly noteworthy in light of previous findings (see Section 1.4) showing that phonological processing is not an isolated skill, but is influenced by broader cognitive functions. Specifically, working memory, attention, and executive functioning have been shown to support the efficient access and manipulation of phonemes. (Cardoso et al., 2013; Farrar & Ashwell, 2012; Gathercole et al., 2006; Gathercole & Baddeley, 1995; Ortiz-Mantilla et al., 2010; Ramus & Szenkovits, 2008; Tal & Shaul, 2024; Yoncheva et al., 2014). Therefore, the evidence that lexical stress representation in connected speech is not impaired per se—but that reduced detection of weak syllables may reflect a compensatory mechanism related to working memory

impairment—raises further questions. Specifically, it remains unclear whether reduced acoustic sensitivity to lexical stress might explain difficulties in phonological representations in ecological contexts or whether deficits in cognitive resources might be the key underlying factor. In this context, musical training represents an additional factor that may modulate individual performance. Evidence suggests that extensive music training can enhance phoneme perception, acoustic sensitivity, and beat-based rhythm processing (Degé & Schwarzer, 2011; Kraus et al., 2014; Tierney & Kraus, 2013; Flaugnacco et al., 2015), thus providing compensatory support for individuals with DD (Rathcke & Lin, 2021; Weiss et al., 2014; Zuk et al., 2018). Consequently, unmeasured variability in participants' musical background may contribute to differences in phonological and lexical stress processing, thereby obscuring the interplay between these domains.

To enhance our understanding of the interplay between lexical stress and phonological representations, the current study examined the influence of syllabic prominence perception on phonological identification within spoken, rather than synthesized, nonwords in a phoneme monitoring task, providing an ecologically valid assessment of phonological representations and access processing (Foss & Swinney, 1973; Wade-Woolley et al., 2022). In doing so, it accounted for acoustic sensitivity across both phonology and lexical stress. Italian was selected as the language of study due to the prominent role of durational cues at both levels, while prior musical training was controlled for as a confounding factor, given its potential ameliorating effects on auditory and phonological processing (Braz et al., 2021; Degé & Schwarzer, 2011; Kraus et al., 2014; Senkal & Muhtar, 2021; Sofologi et al., 2022; Tierney & Kraus, 2013). The study focused on phonological contrasts encoded by multiple acoustic cues—pitch, intensity, duration, and syllable rise-time—which naturally co-occur and vary in connected speech. Specifically, we introduced phonological contrasts that are both relevant and well-attested in Italian phonology. In particular, geminate–singleton consonant contrasts were included, as they are primarily marked by segmental duration in Italian (Di Benedetto, 2000; Di Benedetto & De Nardis, 2021; Einfeldt et al., 2019; Mairano & De Iacovo, 2020). We also included lexical stress contrasts, which are typically cued by variations in pitch and intensity (Caccia et al., in preparation; Bertinetto, 1980; D'Imperio & Rosenthal, 1999; Ferrero, 1972). Additionally, obstruent–sonorant distinctions were considered, as they largely rely on intensity differences and spectral energy distribution (Albano Leoni & Maturi, 2018). The acoustic correlates underlying these contrasts—namely pitch, intensity, duration, and syllable rise-time—were systematically examined in our stimuli prior to analysis, to ensure alignment with established descriptions in the literature. To account for the alternative hypothesis that cognitive resources might better explain phonological difficulties in DD, the role of working memory and shifting attention was examined in parallel to acoustic sensitivity, both as potential mediators of phonological performance.

The present study expands the overarching *Lexical Stress Sensitivity Hypothesis*, assuming not only that phonological representations are impaired due to reduced sensitivity to the acoustic cues encoding lexical stress representations, as predicted by the temporal sampling framework (Goswami, 2011), but also further hypothesizing that this reduced acoustic sensitivity extends to the segmental level (Tallal, 1980). More specifically, we predicted that Italian participants with DD would exhibit reduced sensitivity to the gemination contrast compared to TD participants (cf. Angelelli et al., 2016). This reduced sensitivity is expected to be more pronounced for obstruents than for sonorants (Vandermosten et al., 2010) and for strong syllables compared to weak ones given the more extended rise-time in strong syllables compared to weak ones (Leong et al., 2011). If the deficit is acoustic in nature, the performance of DD participants will be best predicted by variability in one or more acoustic cues that encode the linguistic contrasts at hand, including duration, fundamental frequency, intensity, and rise-time. Additionally, this hypothesis predicts that participants who have received musical training will perform better, due to its ameliorating effects on acoustic sensitivity (Braz et al., 2021; Degé & Schwarzer, 2011; Kraus et al., 2014; Miendlarzewska & Trost, 2014; Senkal & Muhtar, 2021; Sofologi et al., 2022; Tierney & Kraus, 2013). As an alternative hypothesis, further expanding the *Cognitive Mediation Hypothesis*, we expected that the fewer cognitive resources available—specifically in terms of attentional control and working memory capacity—the poorer the phonological performance (Lallier et al., 2010; Ramus & Szenkovits, 2008)

## 2.2.1 Method

### 2.2.1.a Experimental Materials

An Italian version of the phoneme monitoring task (Bogliotti et al., 2008; Breier et al., 2001; Foss & Gernsbacher, 1983; Foss, 1969; Foss 1973; Rathcke & Lin, 2021; Smith & Rathcke, 2017) was created for the purposes of the present study. Eighty Italian polysyllabic nonsense strings were designed (e.g. [segora' minu], [bipoza' viba]). Thirty-two strings contained a target embedding. Target phonemes included obstruents ([p], [t]) and sonorants ([m], [l]). They could appear either as a singleton (16 stimuli, e.g. [bipoza' viba]) or as a geminate (16 stimuli, e.g. [bri**pp**ona' fiba]). Most target strings (90%) consisted of 5 syllables; the rest consisted of 4 syllables in total. The occurrence of prominence was varied such that an equal number of target phonemes were placed in prominent/strong (e.g. [segora' **minu**]), or non-prominent/weak syllables (e.g. [zga' vob**more**]). No target occurred in the very first or the very last syllable of the nonsense strings. All target phonemes were onsets of open syllables (CV) while syllables not containing targets were more varied in structure and included all phonotactically permissible combinations in Italian (Vanelli, 2021). To

avoid priming effects while also ensuring comparability of the strings containing singletons vs. geminates, we varied syllable structures and consonants across all pairs of strings while keeping the same pattern of vowels (e.g. [skofena'pori] vs. [kar'donippose]).

The total of 80 stimuli was grouped into eight blocks of 10, each comprising of 4 targets, 2 distractors and 4 fillers presented in a random order. The distractors shared some features with the target. For example, if [no'mozevane] contained a singleton target, a possible distractor had a geminate embedding such as [nimmozar'fina]. An excerpt of the stimuli embedding the target phonemes /p/ and /m/ is provided in Appendix A.

Each target phoneme was monitored for in two blocks. The order of testing blocks was pseudo-randomized, prohibiting one phoneme from being the target of two consecutive blocks. The experiment started with a practice block of 10 nonsense strings containing five /f/-targets, to explain the experimental procedure to participants. At the start of each block, participants were instructed to monitor for one of the target phonemes and press the space bar of a MacBook Air (Retina, 13-inch, 2018) laptop placed in front of them. The laptop was running PsychoPy (Peirce et al., 2019) - a software that recorded participants' responses and their timing. Accuracy scores (0 for a missed target, 1 for a correctly identified target) were subsequently derived from participants' responses. The sensitivity score  $d'$  was calculated in RStudio (RStudio, 2022) to reflect the individual ability to correctly respond to the targets and correctly reject fillers and distractors.

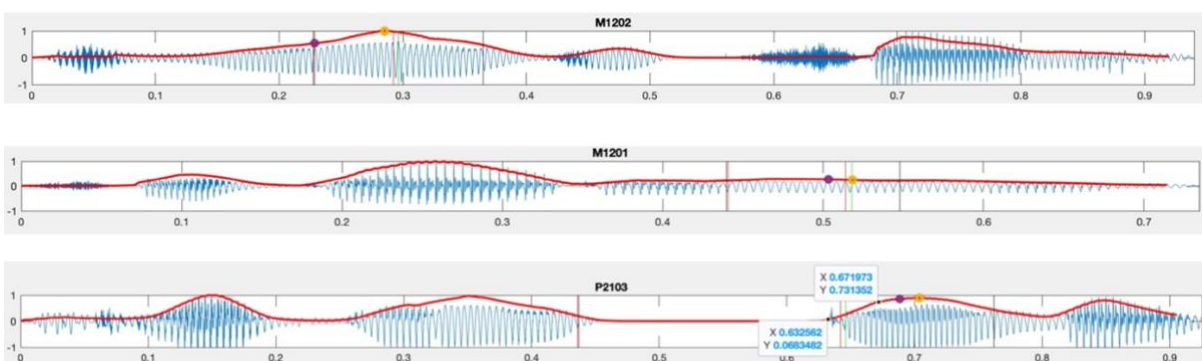
To examine the role of acoustic factors in the phoneme monitoring task, we measured duration, pitch, and intensity of the created stimuli using Praat (Boersma & Weenink, 2007). Specifically, we measured the duration of both target consonants and preceding vowels that often carry the key acoustic cue to the gemination contrast in Italian (Di Benedetto, 2000; Di Benedetto & De Nardis, 2021; Einfeldt et al., 2019; Mairano & De Iacovo, 2020). Compared to singletons, geminates of Italian are typically encoded by longer duration of the consonantal gesture and shorter duration of the preceding vocalic gesture (Di Benedetto, 2000; Di Benedetto & De Nardis, 2021). Duration measurements of vowels and consonants were transformed into a logarithmic scale to normalize their distribution (Baayen, 2008; Crow, 1988). Mean intensity in dB was measured for the duration of each target consonant and the preceding vowel. The latter served as the reference point for amplitude normalization that consisted of the mean intensity values of vowels being subtracted from the mean intensity values of target consonants (Mori et al., 2014). This process yielded a normalized measure of intensity with positive values indicating a higher intensity of target consonants compared to the intensity of preceding vowels. For each target,  $f0$ -values were obtained from midpoints of the preceding and following vowels using a standard Praat-algorithm that set a minimum

$f_0$  to 75 Hz and a maximum  $f_0$  to 600 Hz. The difference between the two values was transformed into the semitone scale using the formula in (1):

$$(1) f_0(st) = 12 * \log \left( \frac{f_{0a}/f_{0b}}{\log 2} \right),$$

where  $f_{0a}$  is the frequency of the preceding vowel and  $f_{0b}$  the frequency of the following vowel. The semitone conversion is commonly used in music for its logarithmic properties that represent the way human auditory system perceives pitch (Mary Zarate et al., 2012). The procedure resulted in the normalized metric (Mori et al., 2014) of pitch change surrounding target consonants, with values close to 0 representing no pitch change, negative values reflecting a pitch fall, and positive values indicating a pitch rise.

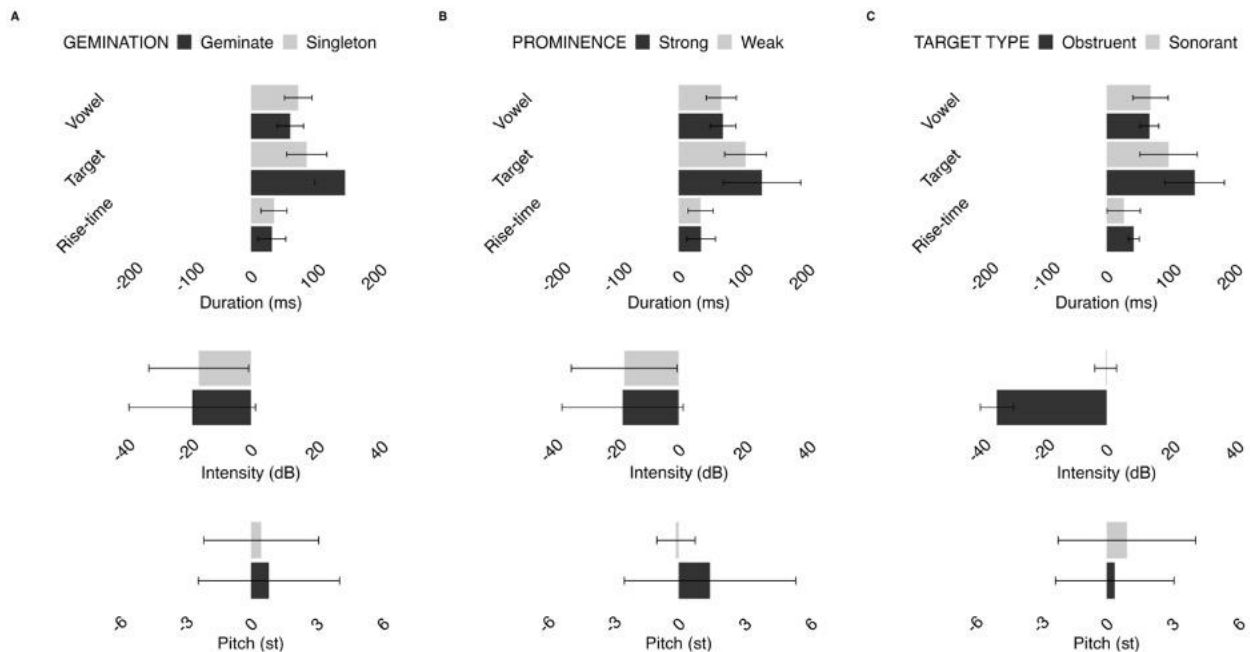
Additionally, we used Matlab (Natick, 2022) to calculate the acoustic rise-times of syllable onsets. The calculation followed the same routines employed in previous research (Rathcke & Lin, 2021; Rathcke et al., 2021). Accordingly, amplitude envelopes were derived by the *envelope* function in Matlab. The function operates on the absolute signal amplitude, smoothing it by applying a spline interpolation with an 11 ms window. The rise-time measured the temporal distance between a local amplitude minimum and a local maximum identified in the smoothed envelope contour round each syllable onset (Goswami et al., 2002; Goswami & Leong, 2013). Forty percent of automatically derived rise-times required manual corrections. Fourteen out of the 24 rise-times that required manual correction showed a tendency toward 0 ms duration (specifically in sonorant targets); the remaining cases displayed a dislocation of the amplitude minimum and/or maximum as illustrated in Figure 1.



**Fig. 1** <sup>3</sup>Illustration of the rise-time calculation in Matlab. Purple dots indicate local amplitude minima; yellow dots indicate local amplitude maxima as identified by the envelope-function. Rise-time is the time spanning the two dots. Vertical green lines indicate vowel onsets of the target syllables. M1202 shows an example that did not require manual correction; M1201 shows an example of a syllable with a flat rise-time that was manually set to 0; P2103 shows an example of a manually corrected minimum and maximum (the place of the dislocation is indicated by x and y coordinates).

<sup>3</sup> Figures and Tables are numbered independently within each study, restarting from Figure 1.

Figure 2 shows the means and standard deviations of all acoustic measurements of the stimuli, comparing their distribution across the three linguistic contrasts of the study (gemination, linguistic prominence, and target type).



**Fig. 2** Overview of the acoustic differences (means and standard deviations) comparing: (A) geminates and singletons (gemination), (B) weak and strong syllables (prominence), and (C) obstruents and sonorants (target type). Target refers to the consonant being monitored for; vowel refers to the nucleus of the syllable preceding the target; rise-time refers to the properties of the amplitude envelope at the onset of the syllable containing the target. Intensity measures the average intensity of the target consonant normalized by the average intensity of the preceding vowel. Pitch reflects the difference between the vowels preceding and following the target.

We conducted linear regression analyses on these data in Rstudio (RStudio, 2022), testing whether or not, and to what extent, the variance seen in the acoustics of the experimental stimuli (plotted in Figure 2) could be predicted by the three experimental factors, including *gemination* of the target consonants (geminate/singleton), *prominence* of the syllable containing the target consonants (weak/strong), and consonant *type* of the targets (sonorant/obstruent). These analyses (summarized in Table 2) confirmed that the observed variability in the isolated acoustic cues was systematic, allowing us to test the predictions of *Lexical Stress Sensitivity Hypothesis*

<i>Acoustic factor</i>	$\beta$	<i>SE</i>	<i>T</i>	<i>p</i>
<b>A. GEMINATION</b>				
<i>Vowel duration</i>	12.84	5.46	-2.34	.02
<i>Target duration</i>	62.14	8.35	15.02	<.001

<i>Rise-time</i>	-0.15	0.23	-0.66	.51
<i>Intensity</i>	-2.02	1.08	-1.86	.06
<i>Pitch</i>	0.34	0.71	0.48	.62
<b>B. PROMINENCE</b>				
<i>Vowel duration</i>	-2443	5543	-0.44	.66
<i>Target duration</i>	26.80	8.35	-3.21	.002
<i>Rise-time</i>	-0.02	0.23	-0.12	.90
<i>Intensity</i>	0.50	1.08	0.46	.64
<i>Pitch</i>	-1.54	0.71	-2.16	.023
<b>C. TARGET TYPE</b>				
<i>Vowel duration</i>	1801	5543	0.325	.74
<i>Target duration</i>	42.34	8.35	-5.07	<.001
<i>Rise-time</i>	-0.74	0.23	-3.17	.002
<i>Intensity</i>	34.08	1.08	31.47	<.001
<i>Pitch</i>	0.55	0.71	0.71	.44

**Table 2.** Summary of best-fit linear regressions examining the role of acoustic cues to (A) gemination (geminate/singleton), (B) prominence (strong/weak), and (C) target type (sonorant/obstruent) in the experimental stimuli.

As indicated, *gemination* (shown in Figure 2-A) was primarily expressed by the duration of target consonants themselves (with geminates being longer) as well as the duration of preceding vowels (with vowels preceding geminates being shorter (cf. Di Benedetto, 2000; Di Benedetto & De Nardis, 2021)). In contrast, variability in rise-time duration, intensity, and pitch did not systematically contribute to the encoding of gemination. The key acoustic correlates of *prominence* (shown in Figure 2-B) included the primary duration of the consonant targets (with longer consonants in prominent syllables (cf. Bertinetto, 1980) and, to some extent, pitch (with a higher than average pitch in prominent syllables (Caccia et al., 2019)). In contrast, neither intensity nor variability in vowel or rise-time duration played a role in the acoustic encoding of prominence in the materials of the present thesis. Lastly, the duration of the target consonant and rise-time, along with intensity, were the main acoustic correlates for *target type* (with obstruents being longer and having longer rise-times and lower intensity than sonorants, see Figure 2-C). In contrast, preceding vowel duration and pitch did

not vary systematically in encoding target type. Please note that shorter rise-times of sonorants are, in fact, indicative of a lack of amplitude variation around the corresponding syllable onsets and are consistently 0 ms for rise-time duration (see Figure 1). Relatedly, sonorants have a relatively high-level of intensity, comparable to that of vowels (resulting in normalized intensity values around 0 dB, Figure 2-C) while obstruents have a substantial intensity drop in contrast to the surrounding vowels (resulting in negative values of normalized intensity, see Figure 2-C). Consequently, and in contrast to the acoustic parameters of pitch and duration, present materials show little meaningful variation in rise-time and intensity beyond the encoding of *target type*. To summarize, while each linguistic contrast relies on a combination of several acoustic cues and shows great variability of the acoustic parameters, duration plays a central role to the encoding of all contrasts under investigation while other acoustic parameters have a relatively minor role to play.

### **2.2.1.b Individual Assessment**

To account for the mediating role of individual cognitive profiles, we included measures of working memory and shifting attention capacity. To assess working memory (WM) capacity, we used the Letter-Number Sequencing (LNS) task from WISC-IV (Orsini, 2012; Wechsler, 2003) and from WAIS-IV (Wechsler, 2008, 2013). This task requires participants to listen to a series of letters and digits and then to reproduce the stimuli with the letters in alphabetical order and the digits in ascending numerical order. In contrast to simple digit span tasks that test the recall of a list of either digits or letters after a brief retention interval that measures primarily the storage aspect of working memory, complex span tasks like WISC-IV and WAIS-IV recruit a secondary operational task (sorting digits and letters) and assesses both the storage and the processing aspects of working memory (Crowe, 2000). It is considered a reliable index of individual working memory capacity (Conway et al., 2005). The final score was the number of correct responses, normed with reference to an existing database. The WISC-IV scores were normed with reference to 14-15 year-old adolescents (Orsini, 2012) while the WAIS I-V scores were normed with reference to 16-21 year-olds (Wechsler, 2008).

To assess attentional capacity, we administered the NEPSY-II Response Set (RS) test (Kemp, 2007; Urgesi, 2011) which measures shifting attention—the ability to adjust focus and adapt perceptual responses to changing environmental demands (Cohen, 2001; Wager et al., 2006). In this task, participants listened to a pre-recorded list of words and were required to touch a specifically colored circle when a designated color word was heard (e.g., “touch the yellow circle when you hear the word red”; cf. Brandt, 1989; Green & Bavelier, 2012). This task evaluates attentional capacity in relation to higher-order executive functions, such as cognitive shifting and inhibition (Kemp,

2007). Scores were standardized using normative data from Urgesi (2011). Given that cognitive resources are considered adult-like by the age of 16 (Matarazzo, 1972), older participants were normed using reference data for 16-year-olds to ensure comparability across age groups.

Finally, questionnaire responses were used to calculate individual music scores following the same procedure as Rathcke and Lin (2021). Accordingly, participants were scored for having music training (0 for “none”, 1 for “some”), active and ongoing music practice (0 for “none”, 1 for “some”), the age they took up their training (2 for an early start before the age of 10, 1 for a later start after the age of 10), the number of years they engaged with music training (one score per year of training), and how many instruments they played (one score for each instrument). The final music score was a sum of all component scores, with higher numbers indicating more music training received by a participant. The scores calculated for the present sample varied from minimally 0 to maximally 21 ( $M = 4$ ), with very few participants scoring high on music training ( $n = 7$ ). This result indicated that the extent of prior music instruction was uniformly limited and consistent among the participants.

Table 3 summarizes descriptive statistics for all individual measures, comparing the three experimental groups. Again, due to the small sample size and non-normal distribution, group-level differences in individual measures were analyzed using the Wilcoxon-Mann-Whitney (WMW) test (Fay & Proschan, 2010; Vierra et al., 2023) for two-group comparisons and the Kruskal-Wallis (KW) test (Hazra & Gogtay, 2016) for multiple-group comparisons using the "stats" package in R (RCoreTeam, 2022). If the KW test was significant, post hoc pairwise comparisons were conducted using Dunn’s test (Dinno, 2015). Results showed that the clinical groups (PD vs. MD vs TD) did not differ with regards to their shifting attention score ( $H(2) = 2.53, p = .282$ ) whereas MD participants showed significantly lower WM scores as compared to control participants MD and TD groups ( $Z = 3.37, p = .002$ ). As far as music training is concerned, no differences were found across groups with regards to the amount of received music training ( $H(2) = 2.19, p = .334$ ).

<b>Group</b>	<b><i>Mdn</i></b>	<b><i>M</i></b>	<b>Min</b>	<b>Max</b>
<i>Shifting attention scores (percentile)</i>				
TD	74	58.6	2	74
PD	43	45.8	2	74
MD	68.5	51.8	2	74
<i>Working memory scores (percentile)</i>				
TD	17.5	28.3	2	65

PD	12.5	17.9	2	50
MD	5	10.3	2	50
<i>Music training scores</i>				
TD	4.5	5.5	0	21
PD	0	3.7	0	14
MD	0	3.4	0	18

**Table 3.** Overview of participant scores on cognitive measures and music training comparing the experimental groups (typical development TD, pure dyslexia PD, mixed dyslexia MD) of the present study.

### 2.2.1.c Experimental Procedure

At the start of the phoneme monitoring task, participants listened to the instructions explained to them by the experimenter (the first author) and displayed by the laptop screen. Subsequently, participants had some time to practice the procedure during a familiarization phase (monitoring for the target phoneme /f/ that was not part of the main experiment). They could clarify any questions remaining after the familiarization with the task phase and determined when they were ready to start the experiment. Good quality headphones (Sennheiser HD 380) were used for the playback of stimuli, with participants being free to adjust the volume to an individually comfortable level.

### 2.2.1.d Data Pre-processing and Statistical Analyses

Individual  $d'$ -values (Macmillan & Creelman, 2004) were calculated for each participant. According to the framework of signal detection theory,  $d'$ -sensitivity serves as a measure of the ability to distinguish between signal and noise during a detection task (Macmillan & Creelman, 2004). The  $d'$ -value is obtained by taking the difference between the z-scores of the hit rate (represented by the proportion of correctly detected targets in relation to all targets) and the false alarm rate (represented by the proportion of false alarms in relation to all distractor targets). A higher  $d'$ -value indicates a superior capacity to differentiate between targets and distractors while a lower  $d'$ -value implies a decreased target sensitivity. In order to calculate  $d'$ -values for each participant, we determined the total number of correct responses (n-hit) versus missed responses (n-miss) and the number of false alarms (n-fa) versus correctly rejected responses (n-cr). These values were then entered into the  $d'$ -prime function within the *Psycho* R package (Makowski, 2018). Using this method, we computed one  $d'$ -value per participant across all targets.

Linear regressions were fit to the resulting  $d'$ -values, testing for (1) a difference between the two clinical groups (PD vs. MD) and (2) a difference between the clinical and the control group (TD

vs. DD). Therefore, *group* was first entered as a predictor with three levels (PD vs. MD vs. TD) and subsequently converted into a two-level factor (DD vs. TD) if there was no difference in the performance of the two groups with DD. This procedure ensured that we could avoid a subdivision of the clinical sample and related power issues if unnecessary (Alosh et al., 2017; Dmitrienko et al., 2016).

Furthermore, we ran logistic mixed-effects regressions (estimated using ML and the BOBYQA optimizer), examining what factors influenced accuracy in the phoneme monitoring task, i.e., the ability to correctly identify targets embedded in the nonsense strings. All responses to a correctly identified embedding were coded as 1, missed embeddings were coded as 0.

Predictors for both models included *music score*, *working memory score*, and *shifting attention score*, whereas only the accuracy model also included *gemination* (singleton/geminate), *target type* (obstruent/sonorant), and *prominence* (weak/strong). We tested for a two-way interaction between these predictors and group.

A third logistic mixed-effects regression model was fitted to the accuracy data using maximum likelihood estimation (ML) and the BOBYQA optimizer. This analysis examined acoustic factors as covariates, including pitch, intensity, duration, and rise time, all of which were normalized as described in Section 2.2, with group as a predictor.

Given some variability in gender and age of the participants across the experimental groups, we additionally checked if age (either as a numerical covariate or as a binary factor contrasting “adult-like”, i.e. 16 and above, and “not adult-like”, after Matarazzo (1972) alongside gender (as a binary factor) may have influenced the results. Additionally, individual average school grade was added as a control predictor in all models as a proxy of IQ (Borghans et al., 2016). To account for the possibility that stimuli and participants may vary in responses, we added *participant* and nonsense *string* as random effects. Maximal random effect structure was retained if the models converged and did not produce singular fit (Barr et al., 2013).

The best-fit regression models were obtained in a backward-fitting procedure. All analyses were conducted in Rstudio (RStudio, 2022) using the library packages *lme4* (Bates et al., 2015), *lmerTest* (Kuznetsova et al., 2017), *psycho* (Makowski, 2018), and *hqmisc* (Quene, 2022).

## 2.2.2 Results

### 2.2.2.a Analysis of $d'$ -sensitivity

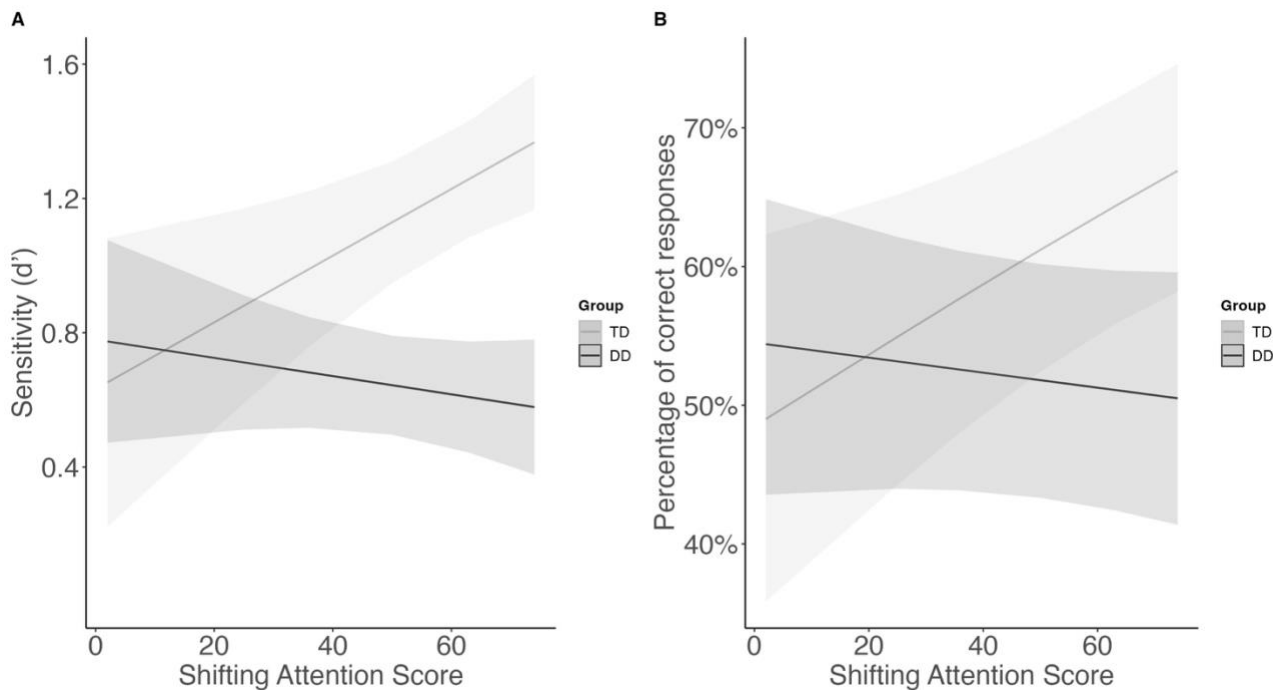
First, linear regressions were fit to  $d'$ -values calculated for participants with MD vs. PD, checking if the two clinical groups differed significantly in their  $d'$ -sensitivity. No significant group difference

was found (MD:  $M = 0.53$ ,  $SD = 0.43$ ; PD:  $M = 0.8$ ,  $SD = 0.54$ ;  $F(1) = 3.03$ ,  $p = .08$  ). Therefore, we ran a linear mixed-effects model comparing  $d'$ -values between the clinical and the control group (DD/TD), examining whether or not the group-level difference was moderated by participants' music experience and cognitive resources. *Age* was fit either as a covariate or as a binary predictor, alongside *gender* (a binary factor) and average school grade (a numerical covariate). The best-fitting model ( $F(3, 66) = 11.13$ ,  $p < .001$ ; shown in Table 4A) retained an interaction of between *group* and *shifting attention score* ( $t(66) = 2.78$ ,  $p = .006$ ), explaining a substantial proportion of variance in the data ( $R^2 = 0.30$ ). Figure 3A visualizes this interaction and shows that  $d'$ -sensitivity of participants with DD remained constant regardless of their individual attentional scores while  $d'$ -sensitivity of the TD participants varied linearly along with their attentional scores. The TD participants of the present sample who measured the lowest attention scores showed a reduced ability to detect targets and reject non-targets, exhibiting  $d'$ -values similar to those of the clinical group. Using *emmeans* (Lenth, 2022) and employing the Scheffé adjustment method for multiple comparisons (Lee & Lee, 2018; Midway et al., 2020), we compared within-group estimates of  $d'$ -sensitivity at 0 vs. 70 of the *shifting attention score*, confirming that DD participants did not differ in their performance on the task ( $t(66) = 0.95$ ,  $p = .34$ ) while TD participants did ( $t(66) = -2.8$ ,  $p = .006$ ). Participant *gender* ( $F(1) = .22$ ,  $p = .64$ ), *age* ( $F(1) = 2.40$ ,  $p = .12$ ) and *average school grade* ( $F(1) = 1.20$ ,  $p = .22$ ) also did not play a role in the task.

### 2.2.2.b Analysis of Accuracy

Having examined  $d'$ -sensitivity (which can only be calculated on an aggregated dataset), we next examined if the interaction between *group* and the acoustic, linguistic, and cognitive factors of interest could explain the variance in the accuracy data, or the general tendency to correctly respond to the consonant targets only. As the two clinical groups did not significantly differ in the overall percentage of their accurate responses (PD:  $M = 40.87$ ,  $SD = 6.60$ ; MD:  $M = 37.79$ ,  $SD = 7.06$ ;  $\chi^2(1) = 1.92$ ,  $p = .17$ ), the group variable was treated as a two-level predictor (percentage of accurate responses of TD:  $M = 45.06$ ,  $SD = 6.31$ ; percentage of accurate responses of DD:  $M = 39$ ,  $SD = 6.9$ ). The best-fitting models of accuracy, whether based on linguistic or acoustic predictors, retained only one interaction of *group* with the *shifting attention score* ( $\chi = 6.60$ ,  $p = .01$ ), similar to the best-fitting model of  $d'$ -sensitivity. The nature of the interaction is visualized in Figure 3B. Replicating the results of  $d'$ -sensitivity, the interaction indicated that accuracy of participants with DD remained stable irrespective of their individual attentional scores while accuracy within the TD group increased linearly with higher attentional scores. Subsequent within-group comparisons of participants with a *shifting attention score* of 0 vs. 70 were performed using *emmeans* (Lenth, 2022) and employing the

Scheffé adjustment method for multiple comparisons (Lee & Lee, 2018; Midway et al., 2020). No difference in phoneme monitoring was found within the DD group ( $z = 1.15, p = .45$ ) while the performance of the TD differed depending on their shifting attention score ( $z = -2.76, p = .005$ ).



**Fig. 3** Estimates of  $d'$ -sensitivity (panel A) and accuracy (panel B) among control (TD) and clinical (DD) participants as a function of their normalized attention score.

In addition, the best-fitting model also retained three main effects, including *gemination*, *target type*, and *prominence*, suggesting a perceptual advantage for geminates (over singletons), obstruents (over sonorants), and targets occurring in strong (rather than weak) syllables. Neither participant *gender* ( $\chi^2(1) = .21, p = .64$ ), nor *age* ( $\chi^2(1) = 1.71, p = .19$ ) or average school *grade* ( $\chi^2(1) = .82, p = .36$ ) helped to significantly improve the fit of the accuracy model. The model best fitting the accuracy data is summarized in Table 4B. It explains a moderate proportion of variance in the data ( $R^2 = 0.21$ ).

<b>(A) <math>D'</math>-sensitivity</b>			
<b>Factors</b>	<b>AIC</b>	<b>RSS</b>	<b><i>p</i></b>
<i>Group * Shifting Attention Score</i>	-94.41	16.67	.005
<b>(B) Accuracy</b>			

	<b>Factors</b>	<b>AIC</b>	<b>LRT</b>	<b>p</b>	
<b>Table 4.</b> of the	<i>Group * Shifting Attention Score</i>	5379.5	6.61	.01	Summary
	<i>Prominence</i>	5390.1	17.15	< .001	
	<i>Gemination</i>	5387.2	14.32	< .001	
	<i>Target Type</i>	5379.2	6.26	.01	

regression models best fitting (A) the  $d'$ -sensitivity data and (B) the accuracy data.

### 2.2.2.c Reliability Check

Given that some participants from the TD group performed comparatively poorly in the task, we examine the possibility of false negatives (i.e., undiagnosed dyslexic cases in the TD group), by conducting a normality test of  $d'$ -values and accuracy responses of the TD group using the R function *Shapiro-test* (RStudio, 2022). The results showed that indeed  $d'$ -sensitivity values were not normally distributed ( $W = 0.92$ ,  $p = .03$ ) whereas accuracy responses were ( $W = 0.95$ ,  $p = .18$ ). We examined the  $d'$ -distribution and identified that it was centered around 1.1 with long tail tendency toward value 2 (Max = 2.2, Min = 0.4), suggesting the likelihood of outliers solely among best performers. This post-hoc analysis indicates that the results of the present study are unlikely to be attributable to the TD group containing a number of clinically unidentified outliers.

To further check for an internal consistency of the task performance, we calculated Cronbach's alpha (Cronbach, 1951; Tavakol & Dennick, 2011) for each stimulus based on accuracy data, using the R library *psych* (Revelle, 2024). The Cronbach's Alpha coefficient of internal consistency ranged from 0.74 to 0.77 across all stimuli ( $Mdn = 0.75$ ,  $M = 0.75$ ). The relatively small range between the minimum and the maximum values of the coefficient as well as the relatively high coefficient values themselves suggest a relatively high level of internal consistency across all stimuli of the study (Cronbach, 1951; Tavakol & Dennick, 2011).

### 2.2.3 Discussion

The present study aimed to extend the overarching Lexical Stress Sensitivity Hypothesis (Goswami, 2011) by investigating whether reduced sensitivity to acoustic cues extends to both prominence (Goswami, 2011) and phonological contrasts (Tallal, 1980) in individuals with DD. Furthermore, it examined whether this reduced sensitivity could account for group-level differences in phoneme identification among 16 Italian adolescents with pure DD, 24 with both DD and dyscalculia, and 30

Italian adolescents with typical development. The potential mitigating effect of music training on these differences was also explored (Braz et al., 2021; Degé & Schwarzer, 2011; Flaunacco et al., 2015; Kraus et al., 2014; Miendlarzewska & Trost, 2014; Senkal & Muhtar, 2021; Sofologi et al., 2022; Tierney & Kraus, 2013).

Alternatively, in alignment with the overarching Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008), the study examined whether group-level differences in phoneme identification could be better explained by deficits in shifting attention and working memory. Dyscalculia was included as an inclusion criterion due to its non-linguistic nature and evidence suggesting a shared linguistic profile (Vellutino et al., 2004). However, given the potentially more severe deficits in the presence of this comorbidity (Jordan, 2007), group-level differences between the two clinical groups were controlled for in the analysis. To do so, we compared the performance of the clinical and control groups on a phoneme listening task adapted for Italian, which involved the identification of geminates versus singletons and obstruents versus sonorants, with targets embedded in strong and weak syllables of non-words. Within the Temporal Sampling Framework, we predicted greater phonological difficulties in phoneme identification for segmental contrasts encoded by duration, along with a significantly reduced facilitatory effect of prominence on target identification within the clinical population.

With regards to the primary hypothesis, the present study provided no evidence to suggest that Italian adolescents with DD had a reduced perceptual ability to make efficient use of naturally variable parameters of acoustic speech signals (such as duration, fundamental frequency, intensity, or rise-time) that encode multiple linguistic functions (such as prominence, gemination, and manner of consonant articulation). Even though the results showed that both groups of DD participants had a lower level of phonological  $d'$ -sensitivity and accuracy compared to TD participants, this group-level difference could not be explained by an inability to process acoustic cues to phonological contrasts as the best-fit model of accuracy did not retain any interactions of group and the acoustic cues of the present investigation (i.e., duration, fundamental frequency, intensity, or rise-time). In addition, lower identification rates in DD were homogeneous across prominent and non-prominent syllables, as well as across geminates and singletons or obstruents and sonorants, regardless of the differences underlying their acoustic cues. Notably, no significant differences were found in sensitivity ( $d'$ ) and accuracy between the two clinical groups in the initial comparisons, thus supporting previous proposals of a shared linguistic profile (Vellutino et al., 2004). As a consequence, to increase the power and reliability of the findings, they were treated as a single clinical group.

There may be several reasons as to why the *Lexical Stress Sensitivity Hypothesis* (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013) is not supported by the present

results. First, linguistic backgrounds of dyslexic participants (here, Italian) differ across studies, with a majority of prior investigations focusing primarily on English (Leong et al., 2011; Tallal, 1980), French (Casini et al., 2018; Werker & Tees, 1987), or Dutch (Vandermosten et al., 2010) speakers. Accumulated evidence indicates that native language(s) may play a role in the phenotypic manifestations of language-related disorders (Bortolini & Leonard, 1996; García et al., 2023; Ziegler et al., 2010). Second, disparities in methodologies employed across studies could also contribute, in part, to the observed variability in the available findings. Some studies lean more heavily on metacognitive tasks (Caccia et al., 2019), potentially introducing a bias stemming from an increased cognitive load (Protopapas, 2014; Ramus & Ahissar, 2012), while others opt for stimuli which more strongly resemble the context of natural speech, aiming at capturing phonological processing during real-world, online perception and processing (Rathcke & Lin, 2021; Virtala et al., 2020). However, it is also important to highlight that not many studies examine the role of cognitive factors during linguistic tasks, though recent findings strongly suggest a crucial role of cognitive resources in DD (Bégel et al., 2022).

With regards to the mediating role of cognitive deficits over phonological deficits, our analyses of both accuracy and  $d'$ -sensitivity consistently showed an interaction of group and shifting attention score. Specifically, participants of the two groups (TD vs. DD) differed in how well they could shift the attentional focus for phonological processing. While dyslexic participants with a higher shifting attention score did not show better phoneme monitoring performance in comparison to DD participants with a lower attention score, the group of TD participants demonstrated a strong linear relationship between shifting attention and accuracy in identifying target embeddings. This result suggests that phonological processing in individuals with DD might receive less support from attentional resources and executive functions than it does in typically developing (TD) individuals. Such dissociation of phonology and cognitive resources was not observed in TD participants whose performance was very comparable to that of DD participants when their attentional resources were limited.

This finding supports the *Cognitive Mediation Hypothesis* (Lallier et al., 2010; Ramus & Szenkovits, 2008) of phonological deficits in DD. However, the nature of this mediation does not fully align with previous accounts of DD that assume a moderating role of shifting attention. Specifically, the Sluggish Attentional Shifting Hypothesis of dyslexia (Hari & Renvall, 2001) suggests that individuals with DD may have difficulty shifting their attention from the preceding to the following temporal event in connected speech. The key issue of this proposal in the context of the present results is that target duration varied across our stimuli and phonological categories, with many of them being encoded by slow rather than rapid acoustic durational changes.

A possibly more convincing explanation may be provided by a recent proposal that DD is linked with brain connectivity deficits which extend to the phonology domain (Habib, 2021; Lou et al., 2019; Paulesu et al., 1996). This idea was first advanced by Paulesu et al. (1996) who examined brain activity in well-compensated dyslexic adults during a series of phonological and short-term memory tasks. The results revealed that DD participants differed from the TD group in that phonological processing led to the activation of isolated brain regions but without a cross-region, simultaneous co-activation. The authors concluded that impaired phonological abilities in DD could be accounted for by a dissociation between anterior and posterior language areas. Recent neuroimaging studies provided more extensive evidence in support of the hypothesis that individuals with DD show a remarkable disconnection in local brain networks within the left hemisphere (Lou et al., 2019; Yan et al., 2021). In light of this hypothesis, the impaired phoneme monitoring ability observed in dyslexic participants of the present study could potentially be attributed to a reduced ability to establish, enhance, or sustain appropriate neural connections between networks responsible for the interaction between attention and executive function capacities and phonology.

Nevertheless, there may be a further alternative explanation to the present finding. Given that some studies highlight the role of experiential factors in DD, especially the amount and frequency of reading (Huettig et al., 2018; Roberts et al., 2015; Willcutt et al., 2001), it could be argued that TD and DD participants of the present study may have differed in their individual reading experience which had not been quantified as part of the study protocol. Extensive reading experience has been shown to exert a positive influence on attention (Roberts et al., 2015) as well as phonology (Huettig et al., 2018; Masonheimer et al., 1984), thus being a relevant factor to consider in the context of the present study. However, a potential group-level difference in individual reading experience cannot fully explain why DD participants with high shifting attention capacities would nonetheless encounter difficulties during phoneme monitoring. At the same time, individual differences in reading experience could potentially account for the present observation that the phoneme monitoring performance of our control participants was as low or even lower than the performance of our participants with DD when their shifting attention scores fell below the 10th percentile. This observation indicates that more extensive individual measures, such as IQ, and background questionnaires are required to elucidate the multidimensional nature of reading disorders (Lachmann and Bergström (2023).

With regards to the compensatory effect of music training (Miendlarzewska & Trost, 2014; Mina et al., 2021; Rathcke & Lin, 2021; Weiss et al., 2014; Zuk et al., 2018), the present study did not identify music score as a significant predictor in our models. However, future research with a

sample that better represents variations in music training may help clarify its role, reducing the risk of power-related biases.

In conclusion, this study provides evidence that Italian adolescents with DD are indeed associated with issues in phonological processing and awareness (Ramus & Szenkovits, 2008; Snowling, 2003; Tallal, 1980; Thomson & Goswami, 2010; Vellutino et al., 2004). However, these issues cannot be attributed to difficulties associated with the decoding of acoustic cues that give rise to prominence or segmental contrasts as previously suggested (Casini et al., 2018; Goswami, 2011; Masterson et al., 1995; Tallal, 1980; Vandermosten et al., 2010). Instead, the results of the present study indicate that phonological deficits in adolescents with Italian DD may be associated with an inefficient allocation of attention and executive functions resources to the decoding of phonological contrasts. This reduced ability of using these cognitive resources for phonological processing was equally observed in participants with pure and mixed DD, suggesting a shared linguistic profile across the two subtypes of dyslexia (Vellutino et al., 2004). This specific mediating role of cognitive resources in phonological identification aligns with recent proposals suggesting a brain connectivity deficit in DD (Cui et al., 2016; Lou et al., 2019)

### **2.3 Study 2: Acoustic Sensitivity to Lexical Stress in Adolescents**

A growing body of research suggests that individuals with DD may experience difficulties in perceiving lexical stress across the lifespan, likely due to reduced sensitivity to the underlying acoustic cues (Caccia & Lorusso, 2020; Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Muneaux et al., 2004). However, much of the supporting evidence comes from studies utilizing meta-linguistic tasks, which place demands on working memory by requiring participants to retain the acoustic representation of stimuli before making a judgment (Caccia & Lorusso, 2020; Caccia et al., 2019; Cumming, Wilson, & Goswami, 2015; Cumming, Wilson, Leong, et al., 2015). Given that deficits in working memory and other cognitive resources are frequently reported in individuals with DD, it remains unclear to what extent these factors contribute to the observed difficulties in lexical stress perception (Facoetti et al., 2003; Gathercole et al., 2006; Jednoróg et al., 2014; Lewandowska et al., 2014; Varvara et al., 2014).

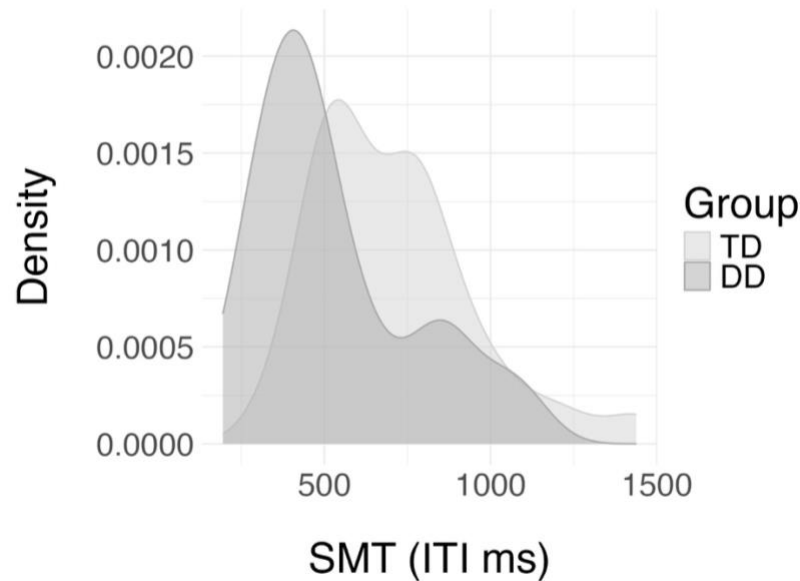
The need to investigate the lexical stress deficit by alternative means and with more naturalistic materials has been highlighted in previous research (Rathcke and Lin (2021). Participants' ability to synchronize with the alternation of strong and weak syllables of natural connected speech was evaluated by means of a finger tapping paradigm (Rathcke & Lin, 2021; Rathcke et al., 2021). This methodological approach is underpinned by evidence suggesting that the perception of rhythm

tends to elicit sensorimotor coupling – i.e., motor synchronization to an auditory rhythm – which can be reliably investigated by using finger tapping (Bégel, Dalla Bella, et al., 2022; Colling et al., 2017; Leong & Goswami, 2013; Rathcke & Lin, 2021; Rathcke et al., 2021; Taha et al., 2022). Compared to metacognitive tasks, the sensorimotor synchronization (SMS) paradigm reduces cognitive load and may therefore serve as a more reliable indicator of speech rhythm perception, especially in clinical populations with a high prevalence of potential working memory deficits (Chen et al., 2023; Protopapas, 2014; Sweller et al., 1998). Additionally, the use of non-constrained, variable stimuli, such as natural sentences, offers a relatively high level of ecological validity compared to temporally manipulated or otherwise rhythmically constrained or simplified stimuli used in previous research. Previous findings collected by means of this paradigm revealed that rhythmic performance of adult English participants with and without DD did not differ in strong syllables but diverged in weak syllables, showing significantly lower likelihood of synchronization with weak syllable nuclei in the dyslexic group as compared to the TD group (Rathcke & Lin, 2021). Notably, the group difference was not predicted by any acoustic measures derived from sentence stimuli, including rise-time. Given that the tendency toward lower SMS likelihood was also found in musically trained participants of the study, the authors interpreted the group difference between dyslexic and typically developing participants as a compensation strategy rather than an indicator of a lexical stress deficit. However, existing evidence based on synchronization with strong-weak non-linguistic beats indicates that individuals with DD tend to exhibit lower SMS accuracy and less anticipation than their typically developing, age-matched peers (Pagliarini et al., 2020; Rossi et al., 2023; Thomson & Goswami, 2008; Wolff, 2002). For instance, Thomson and Goswami (2008) in a study on 10-year-old English-speaking children found that those with DD demonstrated reduced consistency in their tapping intervals when synchronizing with rates of 2 Hz or 2.5 Hz, but not with 1.5 Hz. Given that 2 Hz corresponds to the typical rate of lexical stress alternation in speech (Goswami, 2019), the authors interpreted these findings as indicative of a lexical stress processing deficit.

These findings raise questions about whether difficulties in SMS among individuals with DD are directly linked to reduced lexical stress sensitivity and, more broadly, the nature of this impairment. Specifically, it remains unclear whether these difficulties stem from inefficiencies in processing the acoustic cues that signal increased prominence or from challenges in retrieving linguistic information in the presence of reduced acoustic salience.

To further complicate the picture, as it can be seen in Figure 1 taken by (Rossi et al., 2024), individuals with DD exhibit a faster spontaneous motor tempo (SMT, Bégel, Dalla Bella, et al., 2022; Rossi et al., 2024) which measures the finger tapping rate produced when individuals are asked to tap

with the finger of their dominant hand at their most comfortable tempo without an auditory prompt (Drake et al., 2000; McAuley et al., 2006).



**Fig. 1** <sup>4</sup>Distribution of spontaneous motor rates (SMTs) measured as average duration of inter-tap-intervals (ITIs) in milliseconds. The dark grey distribution shows values measured in the dyslexic group (DD), the light grey distribution shows values of the typically developing participants (TD)

Previous research has shown that individuals achieve more accurate and stable synchronization with auditory rhythmic prompts that align with their SMT (Bégel, Demos, et al., 2022; Kaya et al., 2023; Scheurich et al., 2018). Vice versa, participants exhibit decreased motor stability when engaging with tempos outside of their SMT (Bégel, Demos, et al., 2022). Existing evidence further indicates that individuals with faster SMT exhibit less adaptable synchronization compared to those with slower SMT rates (Bégel, Dalla Bella, et al., 2022; Kaya et al., 2023). Therefore, it remains to be determined whether a lower likelihood of synchronization in SMS reflects reduced sensitivity to lexical stress or prominence alternation, or if it instead stems from differences in SMT. Notably, SMT in trained musicians tends to be slower than in non-musicians (Drake et al., 2000; Scheurich et al., 2018), suggesting a possible role of musical training as a confounding factor mediating the relationship between SMT and SMS.

The present study aims to further refine the Lexical Stress Sensitivity Hypothesis by investigating whether the ability to synchronize with the beat of the sentences among adolescents with and without DD is better predicted by impaired sensitivity to acoustic salience, a key feature of lexical stress (Eriksson et al., 2018), or by differences in spontaneous motor tempo (SMT).

---

<sup>4</sup> Figures and Tables are numbered independently within each study, restarting from Figure 1.

Under the framework of the Lexical Stress Sensitivity Hypothesis we predicted that the ability to synchronize with stressed or accented (i.e., prosodically strong) vs. unstressed, unaccented (i.e., prosodically weak) syllables will be influenced by the natural variability of acoustic cues to prosodic salience (measured as relative F0, duration, and intensity). Accordingly, SMS of participants with DD (measured by synchronization likelihood, accuracy, and variability) will systematically differ from SMS of typically developing (TD) participants, reflecting lower sensitivity to prosodic variability in natural speech.

As an alternative view, here as the Internal Oscillator Hypothesis (Drake et al., 2000; Kaya et al., 2023; McAuley et al., 2006), we predicted that individual SMT will effectively explain the observed variability in SMS with spoken sentences. Faster individual SMT will be linked with weaker SMS-performance on longer timescales (e.g., inter-stress intervals) while slower individual SMT may be linked with weaker SMS-performance on shorter timescales (e.g., inter-vocalic intervals). According to this hypothesis, rhythmic performance in DD compared to TD participants might appear to signify a rhythm deficit affecting specifically longer timescales such as inter-stress intervals (Goswami, 2011; Leong & Goswami, 2013) while essentially reflecting the consequence of different SMT rates at the group level, faster in DD and slower in TD (Rossi et al., 2024). The hypothesis further suggests that SMT may be an individual marker of (motor) rhythm processing abilities, potentially independent of the dyslexic deficit *per se*. In order to disentangle the specific role of SMT, we also considered participants' levels of musical training, given evidence that trained musicians tend to exhibit slower SMTs (Kaya et al., 2023; Scheurich et al., 2018).

To test these (potentially complimentary) hypotheses, we adopted the finger-tapping paradigm that has been previously used in DD research (Bégel, Dalla Bella, et al., 2022; Rathcke & Lin, 2021).

### **2.3.1 Method**

#### **2.3.1.a Experimental Materials**

An Italian version of the SMS task with speech was developed (Rathcke et al., 2021; Rathcke & Lin, 2021). For this task, a corpus of 21 test sentences of variable length (from 9 to 23 syllables) and lexico-syntactic structure was created (see Appendix B for a complete list of sentences). The sentences were recorded in a sound-proof recording studio of the Linguistics Laboratories of the University of Konstanz. The recordings were made by an adult female speaker in her thirties, a native speaker of Northern Italian. The duration of the recorded sentences varied between 1.60 and 3.70 seconds, with some sentences containing pauses between major syntactic constituents (Bertinetto & Magno-Caldognetto; Igras-Cybulska et al., 2016; Mairano et al., 2018; Romano, 2008). Following previous studies of SMS with speech (Rathcke & Lin, 2021; Rathcke et al., 2019, 2021), syllable

nuclei were identified as synchronization anchors, with vowel boundaries being manually annotated by the first author and subsequently checked by the last author. Each vowel was categorized as either strong (i.e., lexically stressed) or weak (i.e., unstressed), based on the metrical status of the syllable that it was part of. The annotations and subsequent acoustic measurements were conducted in Praat (Boersma & Weenink, 2007).

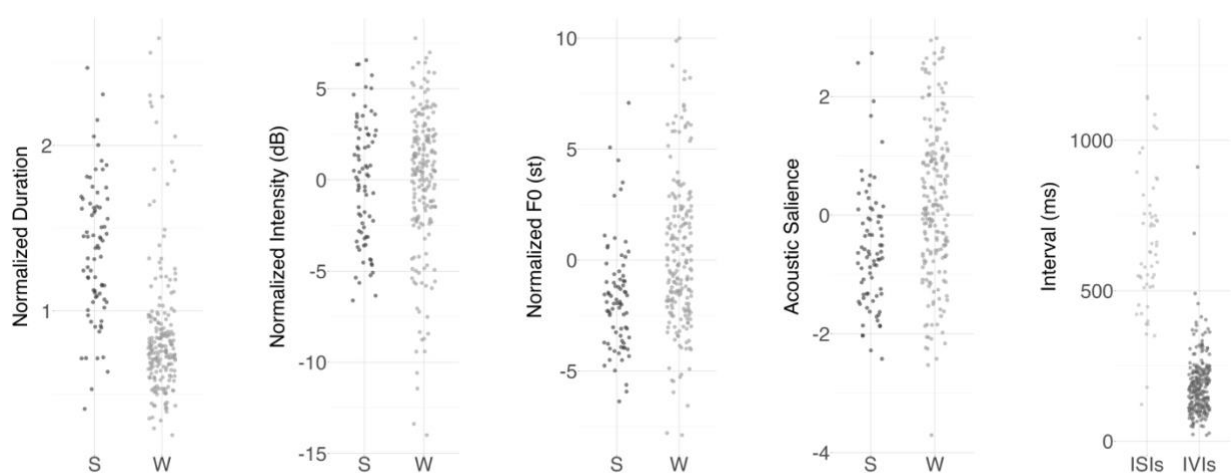
To examine the first hypothesis of the study, we measured total duration (in milliseconds), average fundamental frequency ( $F0$ , in Hz), and average intensity (in dB) of each vowel. Vowel intensity was normalized by subtracting the sentence-specific mean vowel intensity from each individual vowel's value. Resulting values indicate relative intensity of each vowel – i.e., how many dB above (positive values) or below (negative values) the sentence mean each individual vowel measured. Vowel duration was normalized by dividing each vowel's duration by the sentence-specific mean vowel duration. Resulting values indicate relative duration of each vowel – i.e., if it is shorter (<1.0) or longer (>1.0) than the average vowel in the sentence. Normalized vowel-by-vowel variability in  $F0$  was represented on the semitone (st) scale (Pierce, 1983), with the mean sentence-specific  $F0$  being the reference value for the semitone conversion following the formula:  $F0(st) = 12 * \log \left( \frac{F0_n/F0_M}{\log 2} \right)$ , where  $F0_n$  is the average  $F0$  frequency of each vowel and  $F0_M$  the sentence-specific mean  $F0$  within the sentence. Resulting values indicate how much each vowel's  $F0$  deviate from the mean, and if it lies below (negative values) or above (positive values) the mean.

The normalization ensured comparability of all acoustic measurements within and between sentences and gave rise to the following three main acoustic predictors of interest: (1) normalized vowel *duration*, (2) normalized vowel *intensity* (in dB), and (3) normalized vowel  $F0$  (in st). Given that the acoustic measurements may be strongly correlated (Black et al., 2023; Rathcke, Lin, et al., 2024), a factor analysis was performed using the promax rotation and Bartlett's method implemented in the R package "psych" (Revelle, 2024). The analysis indicated that one factor was sufficient to capture the covariance among the acoustic predictors, accounting for 32% of the total variance (SS loadings = 0.95). The factor had the following loadings:  $F0$  (0.72), *intensity* (0.57), and *duration* (-0.32), with their uniquenesses being 0.48, 0.68, and 0.90, respectively. Accordingly,  $F0$  and *intensity* were positively correlated ( $r = 0.41$ ,  $t(273) = 7.42$ ,  $p < .001$ ) while  $F0$  and *duration* ( $r = -0.24$ ;  $t(273) = -3.95$ ,  $p < .001$ ), *intensity* and *duration* ( $r = -0.18$ ,  $t(273) = -3.06$ ,  $p = .002$ ) were negatively correlated. Therefore, only *acoustic salience* scores derived from the factor analysis were used in statistical models reported below.

To test the second hypothesis of the study, durations of inter-vocalic intervals (IVIs) along with the inter-stress intervals (ISIs) were extracted from the manual annotations of vowel onsets. *IVIs* ranged from 20.09 ms to 911.39 ms ( $M = 185.88$  ms,  $Mdn = 173.89$  ms) whereas average ISIs within

each sentence ranged from 122.14 ms to 1339.50 ms ( $M = 666.05$  ms,  $Mdn = 629.78$  ms). Approximately 5% of IVIs and 20% of ISIs included a silent pause. The intra-sentence pauses, demarcating a prosodic break (Bertinetto & Magno-Caldognetto; Mairano et al., 2018) occurred 12 times in total, with durations ranging from 40.93 ms to 616.50 ms ( $M = 211.14$  ms,  $Mdn = 158.77$  ms). Wilcoxon Rank-Sum (WRS) test for asymmetric and nonnormal distributions (Bridge & Sawilowsky, 1999) showed that IVIs were indeed significantly shorter than ISIs ( $W = 424.5$ ,  $p < .001$ ).

As indicated in Figure 2, the materials of the present study showed a high level of variability in all acoustic measurements and their derivatives, as well as in durations of ISIs and IVIs. Table 1 summarizes the results of linear regressions examining the role of these variables in expressing lexical stress. The analyses identified that duration,  $F0$ , and acoustic salience (but not intensity) were the main acoustic correlates of lexical stress in these materials. Accordingly, vowels in stressed syllables showed larger deviations from the sentence mean  $F0$  and duration as compared to vowels in unstressed, weak syllables. Vowels in stressed syllables were longer and showed a larger magnitude of pitch change from the sentence mean (in this case, a substantial pitch fall below the mean). These measurements gave rise to a decrease in the derived acoustic salience values, reflecting primarily the substantial  $F0$ -fall accompanied by an intensity drop as produced by the speaker in most accented syllables. Overall, 67% of all pitch accents were produced as a falling pitch accent (H+L\*) and only 20% were produced as a high pitch accent (H\*). The remaining 13% of accented syllables showed other types of pitch accents (analyzed as L\*, L+H\*, or H+L\*). Lexical stress (and accompanying phrase-level accentuation by means of a pitch accent, (Avesani & Vayra, 2005; Ladd, 2008) further influenced the variability of IVIs which were longer when an interval contained a stressed syllable. In addition, both *IVI* and *ISI* duration was best predicted by the presence or absence of a silent pause within the interval, with those containing pauses being longer (*IVI*:  $t(2,251) = 14.06$ ,  $p < .001$ ; *ISI*:  $t(2,52) = 10.33$ ,  $p < .001$ ).



**Fig 2.** Variability of normalized duration, intensity, F0, acoustic salience, inter-stress intervals (ISI) and inter-vocalic intervals (IVI) measured in the Italian materials of the sensorimotor synchronization task. Normalized measurements were taken in strong, accented (S) and weak, unaccented (W) syllables

<i>Factor ~ lexical stress</i>	$\beta$	<i>t</i>	<i>df</i>	<i>p</i>
<i>Duration</i>	0.49	8.91	273	<.001
<i>Intensity</i>	-0.12	-0.25	273	0.79
<i>F0</i>	-1.92	-4.57	273	<.001
<i>Acoustic salience</i>	-0.77	-4.75	273	<.001
<i>IVI</i>	65.89	6.76	251	<.001

**Table 1.** Summary of linear regressions examining the influence of *lexical stress* on the acoustic variability of *vowel duration*, *intensity*, *F0*, *acoustic salience* as their derivate, and *inter-vocalic intervals (IVI)*. The reference level is weak syllable

### 2.3.1.b Experimental Procedure

Following previous studies (Rathcke & Lin, 2021; Rathcke et al., 2021), the test sentences were looped with 15 repetitions and separated by 500-ms long silent pauses. The presentation order of sentences was randomized for each test session. Participants were asked to synchronize in time with the beat of each sentence loop and to tap the index finger of their dominant hand on a drumming pad placed in front of them. No specific instructions were given on when to start synchronizing or where the beat was located. Task instructions included three sentences for practice, to allow participants to check their understanding and to familiarize themselves with the task before the start of the experiment. In addition, participants performed a series of unpaced tapping tasks examining their ability to produce and maintain simple and complex rhythms (Rossi et al., 2024). For the purpose of the present study, we measured participants' preferred motor tempo by asking them to tap regularly at a rate that felt most comfortable and natural to them. Individual SMTs were then calculated as the mean duration of inter-tap intervals (in ms) that participants produced in this task. All taps were recorded on a KAT KTMP1 drum pad (KATpercussion, 2021) using Logic Pro X running on a MacBook Air 13 2018.

Given a potential link between SMT and cognitive resources (Ladányi et al., 2023; Rossi et al., 2024), we additionally measured working memory capacity and shifting attention of each participant. Working memory was assessed using the letter-number sequencing task from the WISC-

IV (Orsini, 2012) and the WAIS-IV (Wechsler, 2008, 2013). Shifting attention was assessed by means of the response-set subtest of the NEPSY-II battery (Brooks et al., 2009; Urgesi, 2011). Applying the Wilcoxon rank-sum test for asymmetric and non-normal distributions (Bridge & Sawilowsky, 1999) to the cognitive resource data, no significant group-level differences were found for the shifting attention index ( $W = 486, p = .133$ ). However, the clinical group showed significantly lower working memory scores than the control group ( $W = 333, p = .001$ ). *SMT* moderately correlated with working memory scores ( $r(68) = 0.29, p = .015$ ) but not with shifting attention scores ( $r(68) = -0.19, p = .120$ ), indicating that participants with a higher working memory capacity had slower *SMT*.

Prior to the experiment, participants had to fill in an Italian version of the musical training questionnaire used in previous research (Rathcke & Lin, 2021). The questionnaire contained questions about formal music education (coded as 1 for "yes" and 0 for "no"), ongoing music engagement (coded as 1 for active practice, 0 for inactivity), the onset of music education (coded as 2 for the start before age 10, 1 for the start after age 10), the extent of music training (quantified by the total years of training), and the repertoire of music instruments mastered (one point per instrument). The questionnaire data showed that merely half of the study participants ( $n = 34$ ) had received some musical training, with the highest score of 21 for one TD participant. Over 60% of participants in each group had music scores below 7, indicating a generally low level of prior music training among the participants of the present study (TD:  $M = 5.5, Mdn = 4.5$ ; DD:  $M = 3.5, Mdn = 0$ ). Individual music scores also did not correlate with *SMT* ( $r(68) = 0.16, p = .197$ ).

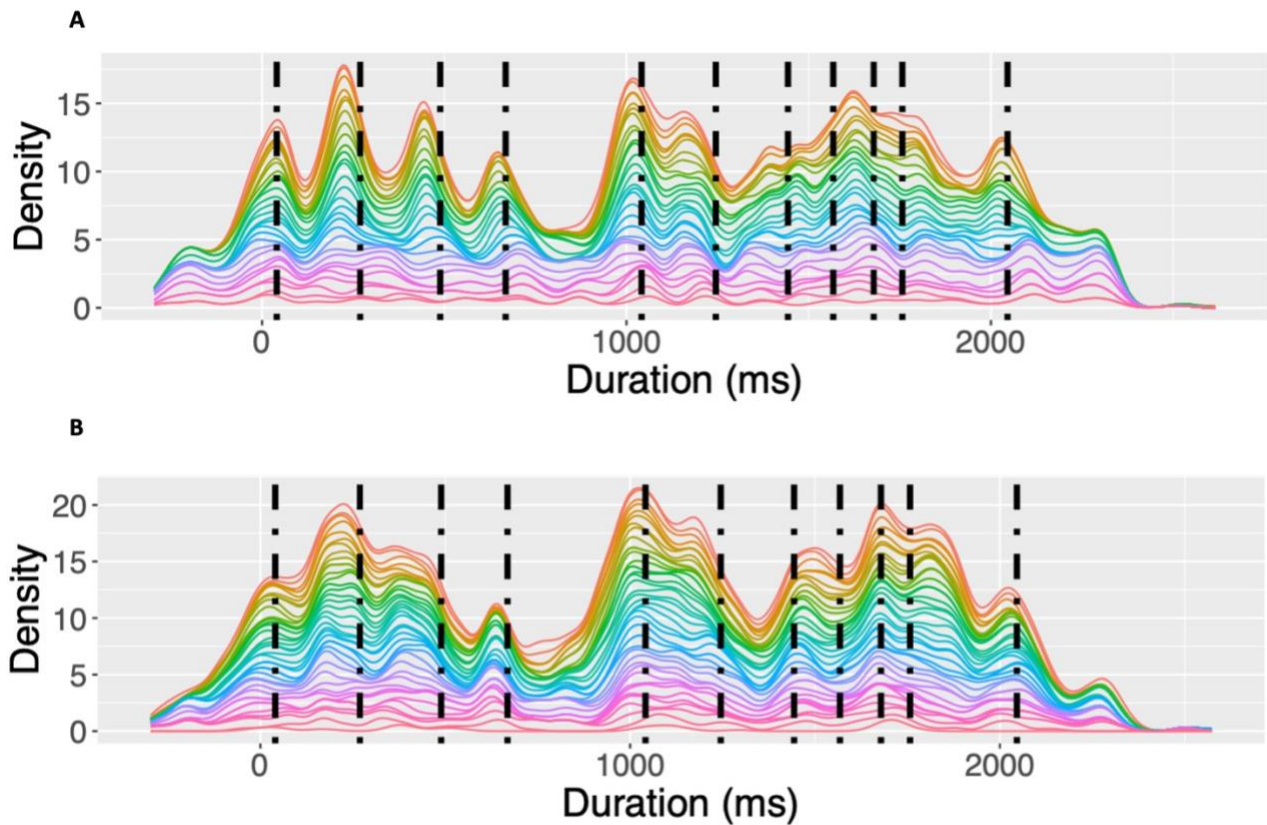
Testing was conducted on an individual basis in a quiet room of the participants' school. The total duration of a session averaged around 50-60 minutes and included breaks whenever necessary. Each participant, along with their guardians, were informed about the purpose of the study and signed a consent form before taking part. The study received ethical approval from the University of Konstanz Ethics Board (IRB statement 05/2021).

### **2.3.1.c Data Pre-processing and Statistical Analyses**

Timings of participants' taps were extracted using MATLAB (Natick, 2022) and adjusted for a systematic time delay of the experimental equipment by subtracting 34 ms from each tap's timing. Two taps within a 5 ms window were considered duplicates and the second one was eliminated. Taps collected in the SMS task were aggregated across sentence repetitions and subjected to Gaussian kernel density estimation using the R package "ggplot2" (Wickham, 2016). Examples of the resulting density plots are shown in Figure 3, comparing SMS of TD and DD participants. The plots indicate that some time points within the given sentence attracted more taps, indicating higher SMS activity in the form of higher local density peaks (here, plotted at the group level). For each sentence and participant, we estimated the temporal locations of the SMS peaks using previously established

procedures (Rathcke et al., 2021). For each sentence, we compared time points of vowel onsets and time points of the estimated SMS peak locations and measured temporal discrepancies between SMS peaks and adjacent vowel onsets. This approach builds on prior findings that vowel onsets tend to serve as reliable synchronization anchors in natural speech (Rathcke & Lin, 2023; Rathcke, Smit, et al., 2024). A syllable nucleus was considered non-synchronized if there was no SMS-peak observed within a  $\pm 120$  ms interval around the vowel onset.

To measure SMS accuracy, we calculated *signed asynchrony* (SA, in ms), capturing how far before or after a vowel onset an SMS peak was located, reflecting anticipatory or reactive nature of taps with reference to a nearby syllable nucleus. Exact synchronization with vowel onsets received the value of 0 ms, SMS peaks ahead of a vowel onset had negative values, SMS peaks following vowel onsets had positive values. SA was then used as the dependent variable in linear mixed-effects regressions. The standard error of SA (in ms) was calculated as  $SE = sd(SA) / \sqrt{n(SMS)}$ , by dividing the standard deviation of SA by the square root of the total number of SMS peaks. Resulting values were used as an index of variability in synchronization, with higher *standard error* (SE) reflecting larger variability or less stable synchronization. SMS accuracy (SA) and SMS variability (SE) were tested as dependent variables in linear mixed-effects regressions. To derive a measure of SMS rate, we examined *SMS likelihood* by determining whether or not every vowel of test sentences attracted a SMS peak. Vowel onsets without an accompanying SMS peak received 0, vowel onsets showing a SMS-peak within the predetermined  $\pm 120$  ms window received 1. This binary coding gave rise to a dependent variable to be tested in logistic mixed-effects regressions.



**Fig. 3** Aggregated SMS-densities obtained with the test sentence “Le attività, le donne le indicano con pazienza” (*The activities, women dictate them patiently*). Panel **A** displays the performance of the control group ( $n = 30$ ), panel **B** shows the performance of the dyslexic group ( $n = 40$ ). The X-axis represents time (0 ms corresponds to the onset of the sentence). Color curves represent cumulative density for each participant within the group. Dashed vertical lines indicate vowel onsets

Adopting the same method for the tap extraction as described above, we derived the timing of participants' taps produced during comfortable tapping. From these taps, *SMT* was calculated as the average interval (in ms) between successive taps (Rossi et al., 2024).

The data were analyzed in Rstudio (Team, 2022) using the packages “lme4” (Douglas Bates, 2015), and “lmerTest” (Kuznetsova et al., 2017). Mixed-effects models included *participant* and *sentence* as random effects, allowing for random slopes for main effects over *participant* as long as no convergence or singular fit issues arose. The best-fit model was established using a backward-fitting procedure (Bates et al., 2015) and estimated using maximum likelihood (Bates et al., 2015).

## 2.3.2 Results

### 2.3.2.a Analysis of SMT and cognitive resources

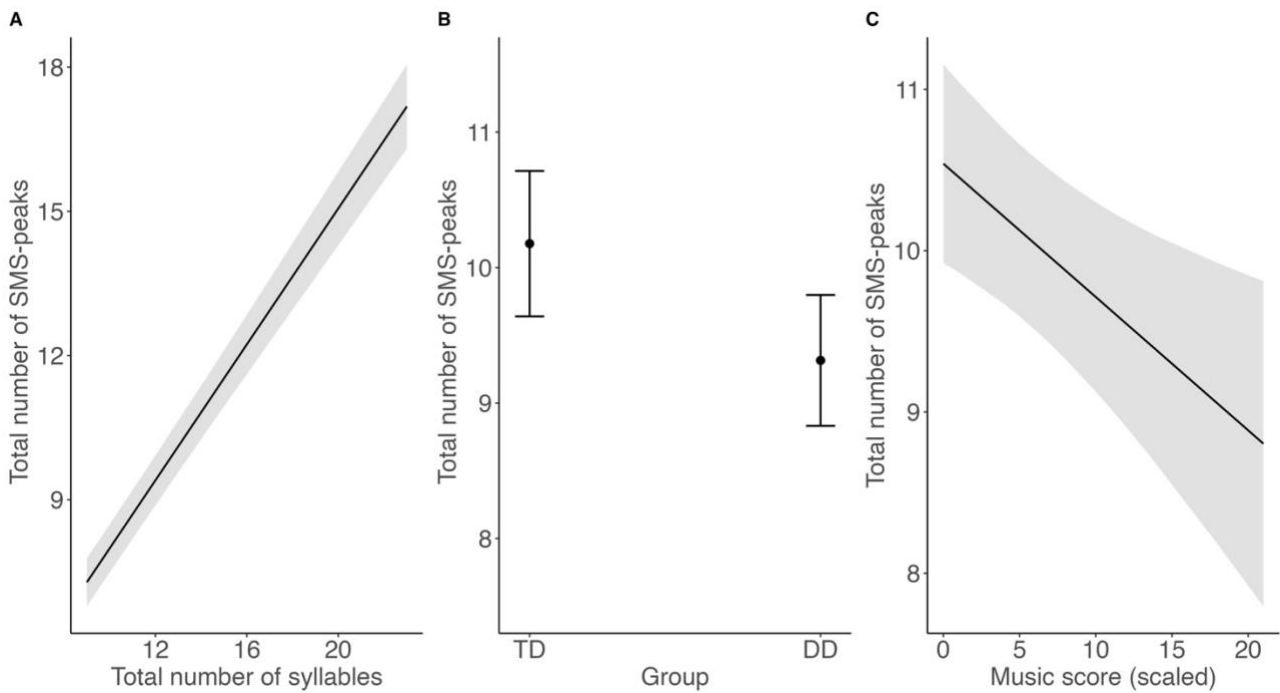
We first examined group-level differences in *SMT* and cognitive resources. As expected, the results of a linear regression confirmed that *group* significantly explained the observed variance in *SMT* ( $F(1,68) = 12.24, p < .001$ ), with DD participants exhibiting a significantly faster *SMT* compared to TD participants (DD,  $M = 532$  ms,  $SD = 241$  ms; TD,  $M = 710$  ms,  $SD = 245$  ms, cf. [Redacted for

Review]). Since both the cognitive data and the residuals of the related linear models violated normality assumptions, (*Working memory*: distribution,  $W = 0.92$ ,  $p < .001$ ; residuals,  $W = 0.95$ ,  $p = .02$ - *Shifting attention*: distribution,  $W = 0.71$ ,  $p < .001$ ; residuals,  $W = 0.80$ ,  $p < .001$ ) we applied the **non-parametric Wilcoxon rank-sum test** (Bridge & Sawilowsky, 1999) to better delineate the cognitive performance across groups. No significant group-level differences were found for the shifting attention index ( $W = 486$ ,  $p = .133$ ). However, the clinical group showed significantly lower working memory scores than the control group ( $W = 333$ ,  $p = .001$ ). Individual *SMT* moderately correlated with working memory scores ( $r(68) = 0.29$ ,  $p = .015$ ) but not with shifting attention scores ( $r(68) = -0.19$ ,  $p = .120$ ), indicating that participants with a higher working memory capacity had slower *SMT*. Individual music scores also did not correlate with *SMT* ( $r(68) = 0.16$ ,  $p = .197$ ).

### 2.3.2.b Analysis of the Domain of Synchronization

Prior to conducting the main analysis, we examined if SMS activity of the participants (measured as the total number of SMS peaks each participant produced in a given sentence) was best predicted by the total *number of syllables* or the *number of stressed syllables*, and if the *number of SMS peaks* differed between the two experimental groups (DD vs. TD) or depended on the individual *SMT* (Rathcke, in preparation). Table 2 A summarizes the best-fit model for SMS peaks.

The results of a mixed-effects regression confirmed that the number of SMS peaks was best predicted by the *number of syllables* ( $F(1,48.82) = 689.33$ ,  $p < .001$ ), but not by the *number of stressed syllables* ( $F(1,18) = 1.63$ ,  $p = .218$ ), indicating that there was a positive, linear relationship between the overall number of syllables and the number of SMS peaks (see Figure 4 A). Additionally, the model fit was significantly improved by the factor *group* ( $F(1,67) = 7.49$ ,  $p = .008$ , Figure 4 B), alongside *music training* ( $F(1,67) = 8.53$ ,  $p = .005$ , Figure 4 C), but not by *individual SMT-rate* ( $F(1,66) = 0.88$ ,  $p = .352$ ). Accordingly, DD participants and musically trained participants showed a tendency toward producing fewer SMS peaks than TD and musically untrained participants. These results suggest that overall, the domain of synchronization was the syllable (and not an inter-stress interval, i.e., the metrical foot) and that it was independent of the individual *SMT* rates.

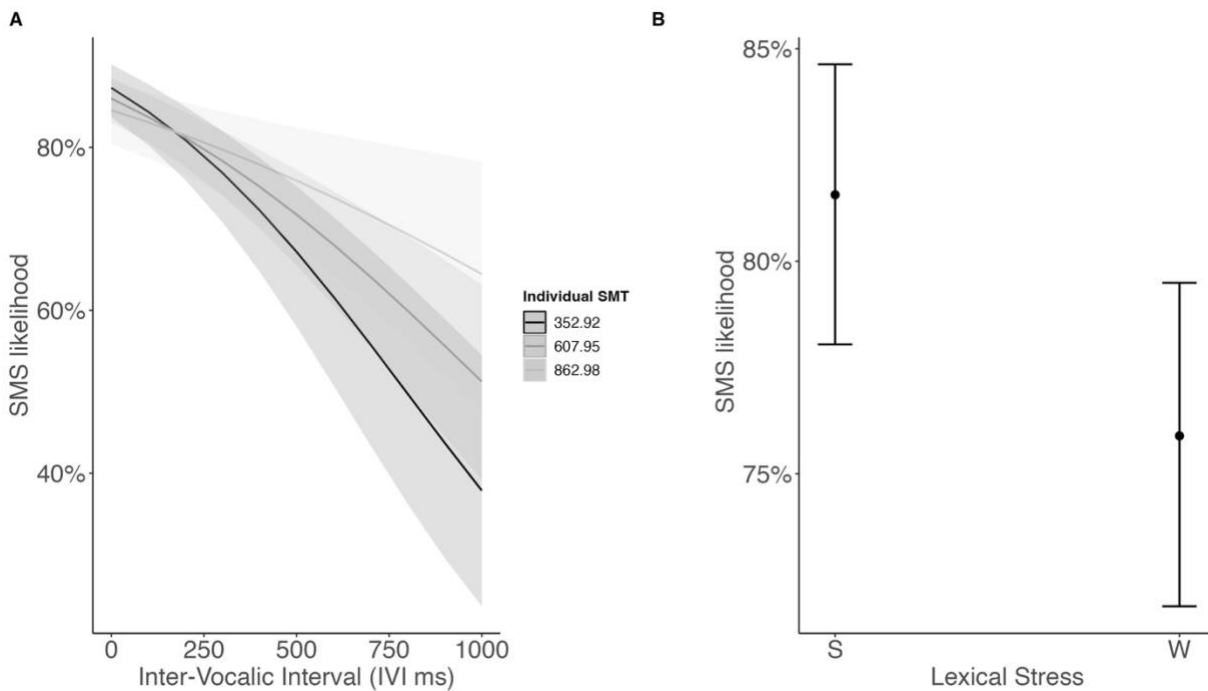


**Fig. 4** Total number of SMS peaks as predicted by (A) the *total number of syllables* within a sentence, (B) participant *group*, and (C) individual *music score*

### 2.3.2.c Analysis of SMS likelihood

To test the predictions underlying the *Lexical Stress Sensitivity Hypothesis* models of SMS likelihood included *acoustic salience* in interaction with *group*. To test the predictions of the *Internal Oscillator Hypothesis* (Drake et al., 2000; Kaya et al., 2023; McAuley et al., 2006), the models included an interaction of the timescale of the domain of synchronization (i.e., IVIs) with *group* and an interaction of *IVI* with *individual SMT*. In addition, *lexical stress* was fit as a predictor to account for linguistic influences on SMS (Rathcke et al., 2021, Rathcke & Lin, 2021) and *music score* as a covariate to account for music training influence on acoustic processing (Hansen et al., 2022; Intartaglia et al., 2017; Mary Zarate et al., 2012). *IVI*, *individual SMT* and *music scores* were scaled and centered around the group mean. Table 2 B summarizes the best-fit model for *SMS likelihood*.

The best-fit model of *SMS likelihood* retained the interaction of *IVI* and *individual SMT* ( $\chi^2 = 6.87, p = .008$ ), but not the interaction of *IVI* and *group* ( $\chi^2 = 2.25, p = .13$ ). Figure 5 A illustrates the significant interaction, showing that participants with the fastest individual SMT demonstrated the lowest likelihood of vowel synchronization when aligning with IVIs exceeding 300 ms. In the stimuli of the present study, IVIs on timescales of 300 ms or longer were the intervals containing a pause or a strong, accented syllable.



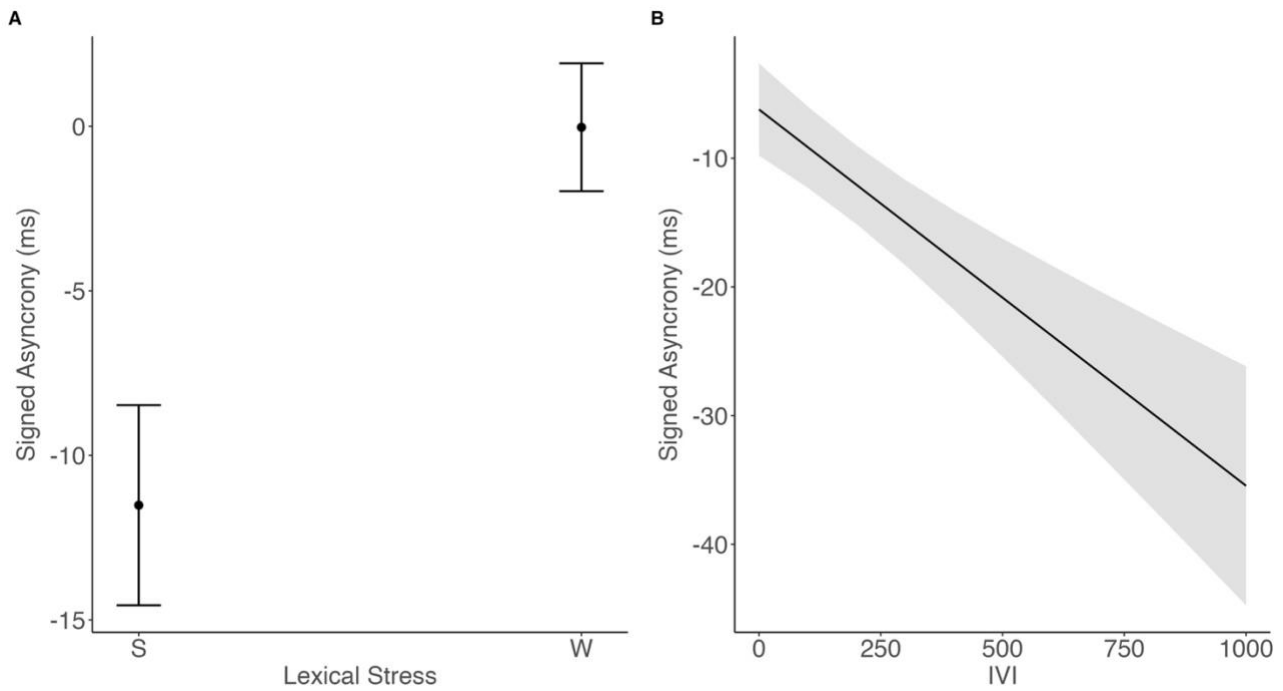
**Fig. 5** SMS likelihood estimates as predicted by (A) an interaction of *inter-vocalic interval (IVI)* duration and *individual SMT* and (B) *lexical stress*

The interaction between *group* and *acoustic salience* was not significant ( $\chi^2 = 1.92, p = .16$ ). There was also no significant main effect of *group* ( $\chi^2 = 2.73, p = .09$ ). However, *lexical stress* (as a main effect and a random slope over *participant*) was a significant predictor ( $\chi^2 = 15.84, p < .001$ , see Figure 5 B).

### 2.3.2.d Analysis of SMS accuracy

Again, we tested for an interaction of acoustic salience and group, to examine the Lexical Stress Sensitivity Hypothesis. We further tested for an interaction of IVI with *group* and IVI with *individual SMT*, to examine the *Internal Oscillator Hypothesis* (Drake et al., 2000; Kaya et al., 2023; McAuley et al., 2006). *Lexical stress* and *music score* were included as control factors. Table 2 C summarizes the best-fit model of signed asynchrony as a measure of accuracy.

The best-fit model of SMS accuracy produced a main effect of *lexical stress* ( $F(1,63) = 37.03, p < .001$ ), showing that strong syllables were anticipated while weak syllables were not, or to a lesser extent (Figure 5-A). Neither the interaction of IVI with *individual SMT* ( $F(1,64) = 3.73, p = .06$ ) nor IVI with *group* ( $F(1,64) = 2.31, p = .13$ ) significantly improved the model fit, though IVI was retained as a main effect ( $F(1,64) = 28.83, p < .001$ , see Figure 5 B). Accordingly, vowel onsets occurring on longer timescales showed more anticipation (see Figure 5 B). The effect of *group* was not present either in interaction with *acoustic salience* ( $F(1, 10859) = .50, p = .47$ ), or as a main effect ( $F(1,70) = 3.38, p = .07$ ).



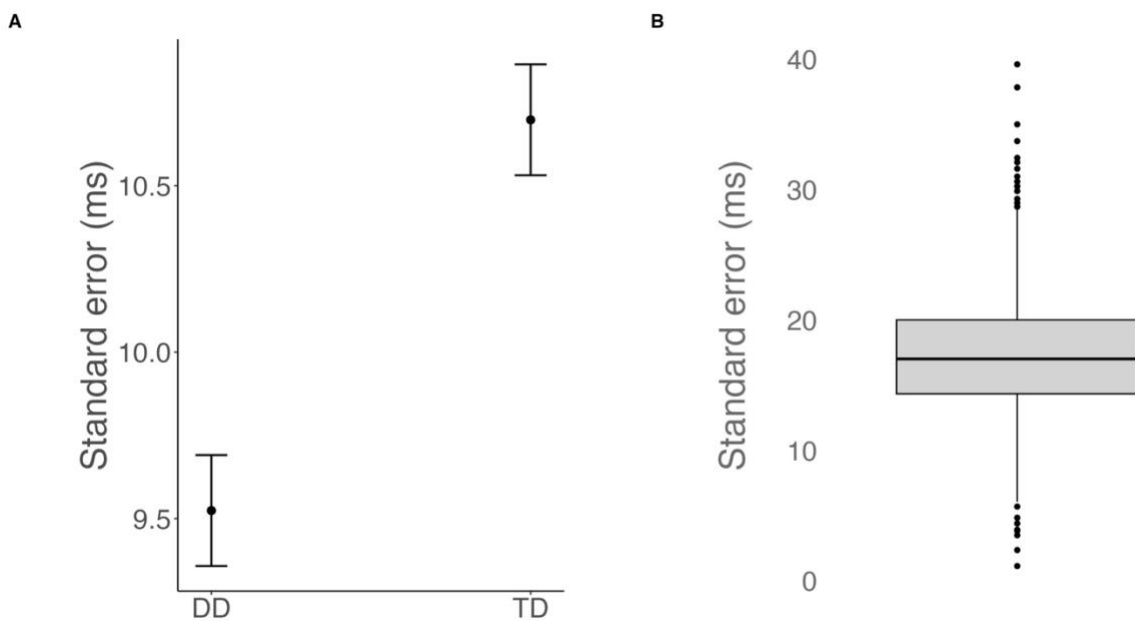
**Fig. 6** SMS accuracy estimates as predicted by (A) *lexical stress* and (B) *inter-vocalic interval (IVI)* duration.

<b>A. SMS peaks</b>			
	<i>Sum Sq</i>	<i>F</i>	<i>p</i>
<b>Total number of syllables</b>	153.45	689.33	<.001
<b>Group</b>	1.67	7.48	.007
<b>Music score (scaled)</b>	1.89	8.53	.004
<b>B. SMS Likelihood</b>			
	<i>AIC</i>	$\chi^2$	<i>p</i>
<i>IVI * SMT</i>	18290	6.87	.008
<i>Lexical stress</i>	18298	15.89	<.001
<b>C. SMS accuracy</b>			
	<i>Sum Sq</i>	<i>F</i>	<i>p</i>
<i>Lexical stress</i>	135339	37.07	<.001
<i>IVI</i>	105264	28.83	<.001

**Table 2.** Summary of best-fit mixed-effects regressions examining the role of experimental and control factors on predicting (A) the total number of SMS peaks, (B) SMS likelihood and (C) SMS accuracy

### 2.3.2.e Analysis of SMS variability

Finally, the predictions of the two hypotheses were tested with SMS variability. To test the *Lexical Stress Sensitivity Hypothesis*, we fitted linear mixed-effects models to standard error of asynchrony, which was calculated by syllable and sentence and measured synchronization stability within the dyslexic vs. the control group (by-syllable dataset). The best-fit model retained only the effect of *group* ( $F(1,273) = 122.9, p < .001$ ), with the TD group presenting higher variability compared to the DD group (see Figure 7 A). Neither the interaction between *acoustic salience* and *group* ( $F(1,272) = 0.04, p = .84$ ) nor *acoustic salience* as a main effect ( $F(1,272) = 3.276, p = .07$ ) were significant. To test the *Internal Oscillator Hypothesis*, a linear mixed-effects model was fitted to standard error of asynchrony, which was calculated by participant and sentence and measured synchronization stability across syllables within each sentence (by-participant dataset). Neither the interaction of *group* with *SMT* ( $F(1,64) = 0.08, p = .78$ ) nor the main effects of either *group* ( $F(1,65) = 2.11, p = .15$ ) or *individual SMT* ( $F(1,65) = 0.72, p = .39$ ) were significant. Figure 7 B visualizes the overall distribution of *SE* values, showing that they averaged around 18 ms, with a small confidence interval and a low number of outliers.



**Fig. 7** (A) Estimates of standard error in the by-syllable dataset as predicted by *group*, and (B) distribution of standard error values in the by-participant dataset

### 2.3.3 Discussion

Further exploring the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), the present study aimed to investigate potential

difficulties in lexical stress processing among Italian adolescents with dyslexia in natural connected speech through sensorimotor synchronization. Within this framework, the study hypothesized that processing acoustic salience (i.e., F0, duration, and intensity), a key feature of lexical stress, would be particularly challenging for participants with DD.

Given mixed findings with regards to SMS difficulties in DD (Pagliarini et al., 2020; Rathcke & Lin, 2021; Thomson & Goswami, 2008; Whalley & Hansen, 2006; Wolff, 2002) and the growing body of research suggesting that an internal rhythmic oscillator, reflected in individual spontaneous motor tempo (SMT), may influence SMS (Drake et al., 2000; Kaya et al., 2023; McAuley et al., 2006; Scheurich et al., 2018) along with evidence indicating that SMT is faster in individuals with DD, deviating from typical development (TD), (Bégel, Dalla Bella, et al., 2022; Rossi et al., 2024), we further hypothesized that SMS performance may be driven by individual SMT. This latter hypothesis posits that individuals with a faster SMT (which dyslexic individuals tend to produce in spontaneous tapping tasks, (Bégel, Dalla Bella, et al., 2022; Rossi et al., 2024) would experience challenges synchronizing to events presented at longer timescales. In order to test these hypotheses, the study used a tapping paradigm developed in previous research (Rathcke and Lin (2021), adapting it for Italian.

We first confirmed that Italian adolescents – just as adult English, French, and Japanese participants of previous studies – tend to synchronize with vowel onsets following the syllabic level of natural sentence rhythm (Rathcke et al. 2021, 2024). While we observed no strict 1-1 relationship between the total number of syllables and the number of SMS peaks, the trend toward synchronization with most syllables of a sentence was least pronounced for musically trained as well as for dyslexic participants. Both findings are in line with previous research (Rathcke & Lin, 2021; Rathcke et al. in preparation). Preliminary evidence indicates that musical training may lead to changes in rhythm perception, with skilled musicians attending primarily to longer timescales and higher hierarchical levels of musical rhythm structure (Drake & Penel, 2000). In this context, the observation that dyslexic participants show SMS profiles comparable to those obtained for musically trained participants is remarkable and aligns with the proposal of Rathcke and Lin (2021) of a compensation strategy rather than a deficit. However, the current findings depart from Rathcke and Lin (2021), as we did not find any group-level differences in alignment with less acoustically salient syllables across sentences. Additionally, more acoustically salient syllables led to comparable synchronization between DD and TD groups, further failing to support the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013). Cross-linguistic replication studies with comparable participant samples are needed to shed new light on this issue which has far-reaching implications. If rhythmic difficulties turn out to be under a strong

influence of language environment (cf. García et al., 2023), intervention programs will have to be adjusted to address the specific challenges that an environmental language may pose for the development and the perception of rhythm (cf. Schneider et al., 2022).

By contrast, and in alignment with the Internal Oscillator Hypothesis (Drake et al., 2000; Kaya et al., 2023; McAuley et al., 2006), individual SMT, rather than prosodic cues, accounted for some variance in SMS performance in natural connected speech. Specifically, participants with a faster SMT rate were significantly less likely to synchronize with vowel onsets occurring at longer timescales (i.e., exceeding 300 ms) than participants with a slower SMT rate. At the same time, participants with slower SMT rates did not exhibit poorer SMS performance on shorter IVIs while also showing a slightly reduced SMS likelihood for long inter-vocalic intervals (albeit to a lesser extent than individuals with a faster SMT rate).

These results are only partially aligned with previous findings obtained during SMS with non-spoken auditory prompts (Bégel, Demos, et al., 2022; Kaya et al., 2023; Scheurich et al., 2018) and suggest a more nuanced view on the role of individual SMT in SMS. Instead of a facilitatory effect of SMT when its rate is comparable to the timescale of the auditory prompt, the present study documents a general benefit of a slower SMT rate for synchronization with natural speech. Given the non-isochronous, variable nature of connected speech (Rathcke & Smith, 2015), the finding might be related to lower synchronization adaptability previously observed in individuals with faster SMT (Bégel, Dalla Bella, et al., 2022; Kaya et al., 2023). Results suggest that the relationship between individual SMT and SMS abilities extend beyond a difficulty with the synchronization to the auditory timescales that differ from one's internal tempo. Long IVIs in the present materials occurred in the presence of a strong syllable and/or a pause, introducing further elements of rhythmic variation. Perceptual processing of such long IVIs – particularly those containing lexically stressed syllables – may require a perceptual estimation of relative durations, also known as beat-based timing or the ability to measure time intervals in relation to a consistent rhythmic pattern or beat. Such timing estimation is crucial in musical contexts, where the perception of note alternations and silences relies on the underlying tempo or beat structure (Teki et al., 2012). Increasing evidence suggests that this ability may interact with cognitive skills (Brown & West, 1990; Castellotti et al., 2022) and mental imagery (Becková et al., 2022) while relying on different neural pathways compared to absolute time estimation (Grube et al., 2010). Accordingly, the influence of individual SMT on SMS may be moderated by cognitive resources (Colley et al., 2018; Kim et al., 2023; Spiech et al., 2025) – here specifically working memory capacity – with SMT possibly indicating how efficiently cognitive resources can be allocated to relative time estimation during SMS in the presence of rhythmic variations. This aligns with previous studies highlighting how SMT may be influenced

by IQ (Ladányi et al., 2021) and reflect differences in cognitive resources (Rossi et al., 2024). Accordingly, following previous research (Kaya et al., 2023; Scheurich et al., 2018), the finding of lower synchronization variability in DD compared to TD participants may be a consequence of a tendency for reduced cognitive resources, leading to decreased flexibility in sensorimotor synchronization

Consequently, contrary to the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), SMS in natural speech among adolescents with and without DD cannot be explained by a deficit in processing acoustic salience underlying lexical stress. Instead, individual SMT appears to be a contributing factor. Given the potential link between SMT, time estimation and cognitive resources (Becková et al., 2022; Castellotti et al., 2022; Grube et al., 2010; Ladányi et al., 2021; Rossi et al., 2024; Teki et al., 2012), Given that a faster SMT is a tendency in DD but with overlap with TD participants, it is possible that SMT reflects individual variability in cognitive resources, potentially serving as a marker of SMS adaptability. Since cognitive deficits are frequently reported in DD, this condition may lead to a more pronounced group tendency toward faster SMT compared to TD, albeit without representing a unique marker of the disorder. Nevertheless, we cannot completely rule out potential links of SMT and specific reading deficits as we did not test reading abilities in the present sample. As a result, the challenges experienced by participants with DD in SMS, influenced by their SMT rather than by reduced sensitivity to acoustic salience, further extend the Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008) to the rhythmic domain, to the rhythmic domain, while failing to support the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013) in DD.

### 3. Lexical stress and Phonology in Children with and without DD

Acoustic sensitivity to lexical stress undergoes progressive development throughout childhood, with lexical stress contrasts continuing to refine between ages 8 and 10 (Arciuli & Ballard, 2017; Quam & Swingley, 2014), the age at which Italian children progressively master stress diacritics in writing (Cornoldi et al., 2012). However, the extent to which these developmental changes influence the commonly observed lexical stress deficits in children with DD and their potential impact on phonological impairments remains uncertain. The present two studies contribute to the current research by integrating this discussion and examining lexical stress deficits, their interaction with phonological impairments, and the role of individual cognitive variability in children with and without DD. The findings will be compared with data from an adolescent cohort to further clarify the developmental pathways of these factors while addressing the overarching research questions.

#### 3.1 Experimental Cohort

57 children from different schools in the Milan metropolitan and hinterland areas volunteered as participants in our study. 28 children (including 19 males), aged 8 to 10 years, had a formal diagnosis of DD, based on the diagnostic criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (American Psychiatric Association, 2022). Notably, 4 of the participants had comorbid dyscalculia. However, as DD participants with and without dyscalculia exhibit comparable phonological profiles (Rossi & Rathcke, in preparation), we treated all participants with DD as a single clinical group, referred to as the DD group. A separate group of 29 children (including 19 males) with typical development (TD) in speech, language, and literacy acquisition served as the control group. Both TD and DD exhibited a comparable age (TD group,  $Mdn = 10$ ,  $M = 9.3$  (0.77), range = 8–10; DD group,  $Mdn = 10$ ,  $M = 9.4$  (0.74), range = 8–10;  $W = 418$ ,  $p = .83$ ) as measured by Wilcoxon Rank-Sum (Fay & Proschan, 2010; Vierra et al., 2023).

To participate in this study, participants' IQ had to fall within the normal range, assessed using Raven's Colored Progressive Matrices, a 36-item nonverbal reasoning task with multiple-choice responses (Belacchi et al., 2008; Raven et al., 1998). Scores were normalized into percentile rank according to Belacchi et al. (2008). Additional inclusion criteria required participants to be Italian monolinguals with no developmental comorbidities (e.g., dyspraxia, ADHD, speech and language delays or impairments).

From the resulting cohort, we derived a subset of 55 (28 DD, including 19 males, and 27 TD, including 19 males) participants without eye pathologies, for whom pupillometry measures were applicable and comparable (Bitirgen et al., 2019).

Participants were individually tested at their respective schools, with each session lasting approximately 90 minutes. Breaks were provided as needed. Consent forms were collected prior to testing. Each session began with the phoneme monitoring task and proceeds with the categorical perception of lexical stress task along with cognitive and other rhythmic tasks, the latter not included in the present study. Ethical approval for the study was granted by the Ethics Board of the University of Konstanz (IRB statement 05/2021).

### **3.2 Study 3: Prominence and Phonology in Children: Phoneme Monitoring**

Phonological deficits are among the most commonly reported impairments in DD (Farquharson et al., 2014; Marchetti et al., 2023; Masterson et al., 1995; Noordenbos & Serniclaes, 2015; O'Brien et al., 2020; Snowling, 1995, 2003; Tilanus et al., 2013; Vandermosten et al., 2010; Werker & Tees, 2005). However, the nature of these deficits remains highly debated (Fraser et al., 2010; Lallier et al., 2010; Protopapas, 2014; Ramus & Szenkovits, 2008; Tallal, 1980; Vandermosten et al., 2010). Some studies suggest that the impairment originates at the level of phonological representations themselves (Fraser et al., 2010; Tallal, 1980; Vandermosten et al., 2010), while others propose that the difficulty lies in solely accessing these representations (Lallier et al., 2010; Ramus & Szenkovits, 2008), thus affecting mainly phonological awareness.

A deficit at the level of phonological representations has been linked to reduced acoustic sensitivity to lexical stress (Goswami, 2011; Goswami, Mead, et al., 2013; Leong et al., 2011). However, findings underlying this lexical stress deficit remain mixed and unclear regarding the nature of the impairment, particularly concerning the presence of an underlying acoustic impairment and the nature of these difficulties—whether they are more pronounced in processing stressed or unstressed syllables and the underlying key (Goswami, 2011; Goswami et al., 2013; Mundy & Wood, 2024; Rathcke & Lin, 2021).

Notably, the conscious access to phonemes involved in phonological awareness tasks requires significant cognitive demand (Cardoso et al., 2013; Farrar & Ashwell, 2012; Gathercole et al., 2006; Gathercole & Baddeley, 1995; Ortiz-Mantilla et al., 2010; Ramus & Szenkovits, 2008; Tal & Shaul, 2024; Yoncheva et al., 2014). Working memory, attention, and executive functions seem to be tightly tied to phonological awareness manipulations. Notably, evidence suggests that these cognitive abilities are often impaired in individuals with DD (Barbosa et al., 2019; Cheng et al., 2021; Chutko et al., 2022; Gathercole et al., 2006; Gathercole & Baddeley, 1995; Knoop-van Campen et al., 2018; Lallier et al., 2010; Masoura et al., 2021; Menghini et al., 2011; Ramus & Szenkovits, 2008; Valdois, 2022) and impact phoneme access in DD. However, the cognitive profile of individuals with DD is highly heterogeneous and IQ-dependent (Cowan et al., 2017; Lukov et al., 2015; Menghini et al., 2010). In this sense, cognitive heterogeneity in DD extends beyond the mere presence or absence of specific deficits, encompassing variations in the nature of impairments across cognitive domains as well as their interactions with IQ. Given the evidence linking multiple cognitive abilities to conscious access to phonemes in both typical and atypical populations, it cannot be ruled out that the parallel effect of individual cognitive resources—whether intact or impaired—across different domains may contribute to difficulties in phonological awareness in DD populations.

To answer those research questions, this study aimed to investigate how acoustic salience (Eriksson et al., 2018), a key acoustic feature of lexical stress—here differentiating between prominent and non-prominent syllables—prominence itself and individual cognitive profiles, defined as a combined factor of working memory, shifting attention, and age-adjusted IQ, contribute to group-level differences in phoneme identification embedded in syllabic strings of nonwords among children with and without DD. Targets were allocated more frequently in weak syllables rather than strong ones to further explore difficulties in processing weak syllables. This was done to test, but also to further expand, the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013) as well as the Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008) as alternative explanatory frameworks for phonological difficulties in DD.

To achieve these aims, we examined both behavioral and pupillary responses. Behavioral responses were obtained through a phoneme monitoring task, similar to those administered to Italian adolescents described in Section 2.2 but adapted with reduced overall complexity to be suitable for a younger population. This task was further implemented as it enables a direct assessment of phonological representation integrity and accessibility while implicitly examining the role of acoustic salience in phoneme perception.

Pupillometry measures pupillary variations (Fink et al., 2024; Hoeks & Levelt, 1993; Mathôt, 2018) which, in addition to regulating light intake through the pupillary light reflex, respond to various events (Boswijk et al., 2020; Chiossi et al., 2023; Kinzuka et al., 2020; Kolnes et al., 2024; Liao et al., 2016; Mathôt, 2018; Pichora-Fuller et al., 2016; Piquado et al., 2010; Robison & Unsworth, 2019; Winn et al., 2015; Zarcone et al., 2016) For instance, Liao et al. (2016) found that participants exhibited increased pupil dilation when listening to speech sounds perceived as more salient due to their higher intensity. Similarly, Zarcone et al. (2016) reported greater pupil dilation in response to stimuli judged to stand out due to their lower frequency. Both studies suggest a direct association between acoustic salience and pupil size increase. Additionally, Kinzuka et al. (2020) found that the ability to discriminate between /r/ and /l/ was associated with earlier peak differences in pupil dilation, while Chiossi et al. (2023) observed that pupil dilation correlated with phonological contrast detection when embedded within complex sentences. These findings further support a link between pupil size peaks and phonological processing. Furthermore, pupil dilation has been consistently associated with cognitive processing (Hoeks & Levelt, 1993; Kolnes et al., 2024; Mathôt, 2018; Pichora-Fuller et al., 2016; Piquado et al., 2010; Robison & Unsworth, 2019; Winn et al., 2015). Several studies have highlighted its relationship with attentional mechanisms (Hoeks & Levelt, 1993; Kolnes et al., 2024), arousal and cognitive engagement (Pichora-

Fuller et al., 2016; Piquado et al., 2010; Winn et al., 2015), while Robison and Unsworth (2019) identified a link between pupil size and working memory capacity.

Consequently, pupil size variations appear to be sensitive to both acoustic salience and cognitive abilities crucial for access to phonology in addition to phonological representations per se. For these reasons, they allow for a simultaneous assessment of those abilities. These pupil diameter variations tend to be smaller than those induced by light-to-dark transitions and are typically reported within a range of 0.01 to 0.5 mm, with considerable variability in latency and peak timing depending on the task. However, both Kinzuka et al. (2020) and Chiossi et al. (2023) reported an activation range within 500 ms and a peak approximately around 1 second after stimulus onset.

As pupillary responses unfold over time (Fink et al., 2024; Mathôt & Vilotijević, 2023), this method enables tracking the temporal dynamics of pupil changes during phoneme identification, rather than relying solely on aggregated data, which may reduce statistical power and obscure meaningful effects (Clark & Avery, 1976; Orcutt et al., 1968). Similar to electrophysiological measures, pupillometry captures cognitive fluctuations before conscious perception, making it a reliable and objective tool for investigating phonological processing while minimizing the risk of false negatives. Additionally, it is less time-consuming and more comfortable compared to cortical measures. Notably, just few studies have examined phonological abilities in individuals with DD using pupillometry (Egan et al., 2023).

Following the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013) we predicted that acoustic salience and prominence would mediate group-level differences in phonological accuracy and  $d'$  sensitivity, correlating with differences in pupil size during phoneme monitoring. As an alternative hypothesis, following Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008) we posited that group differences in accuracy and  $d'$  sensitivity could be mediated by individual cognitive profiles, which in turn might be linked to pupil size variations when identifying targets and excluding non-targets in individuals with DD. Similar to our investigation with adolescents, and in alignment with the Temporal Sampling Framework, we controlled for acoustic sensitivity at the segmental level. In so doing, we predicted greater phonological difficulties in phoneme identification for segmental contrasts encoded by duration, along with a significantly reduced facilitative effect of prominence on target identification within the clinical population.

### **3.2.1 Method**

### 3.2.1.a Experimental Procedure

An Italian version of the phoneme monitoring task (Bogliotti et al., 2008; Breier et al., 2001; Foss & Gernsbacher, 1983; Foss, 1969; Foss 1973; Rathcke & Lin, 2021; Smith & Rathcke, 2017) was developed and simplified in both length and complexity compared to the version previously used with Italian adolescents detailed in Section 2.2, to make it suitable for Italian children.

The task stimuli consisted of 64 polysyllabic nonwords, 50% of which contained a target phoneme that was either an obstruent [t] or a sonorant [l], presented as either a singleton or a geminate ([se'tapodeluvi] versus [sepu'marulasi]; [maka'ralutani] versus [muso'laruttadi]). 25% of these target phonemes were embedded in strong syllables, while the remaining 75% appeared in weak syllables, varying in position relative to strong syllables (e.g., following stress: [kaʃeva'teleguni] versus second syllable after stress [febu'miruladi]). An excerpt of the stimuli embedding the target phonemes /t/ and /l/ is provided in Appendix C. This design enabled a more detailed investigation of targets in weak syllables, which are known to be more challenging for individuals with DD (Rathcke & Lin, 2021). Targets were excluded from the first and last syllables. The nonwords consisted of 6 to 8 open syllables (CV) (Vanelli, 2021). The duration of stimuli ranged between 843 and 1,322 ms, with target onset occurring between 116 and 900 ms from the start of each item. Priming effects were controlled by varying consonant and vowel types, strong syllable placement, and target positions. The stimuli were presented in four blocks, each containing eight targets and eight distractors in random order with an interstimulus interval of 1800 ms. At the start of each trial, instructions relating to the target being monitored were provided in both written and oral format. Participants were instructed to focus on one target type at a time.

Prior to the start of the phoneme monitoring task, to account for changes in pupil diameter during the task, each participant was asked to wear Tobii Pro Glasses 3 and follow the system's default built-in one-point calibration (TobiiAB, 2022a). The Tobii Pro Glasses 3 were connected to their respective software on a Lenovo Thinkpad X1 Carbon via ethernet cable. The internal algorithm calculated eye position and pupil size by capturing images of participants' eyes at a sampling frequency of 50 Hz (TobiiAB, 2022a, 2022b). Efforts were made to maintain a consistent viewing distance of approximately 0.7 meters from the monitor and to control artificial overhead lighting, avoiding direct light sources, which would cause reflections on the computer display.

The entire phoneme monitoring task was conducted using PsychoPy (Peirce et al., 2019), a software that recorded participants' responses in conjunction with their reaction times. This was achieved on a separate laptop – a MacBook Air (Retina, 13-inch, 2018) – to avoid technical conflicts with the pupillometry software. A familiarization phase, in which participants practiced monitoring for the target phoneme /f/ (not included in the main experiment), provided an opportunity for

participants to ask questions and indicate when they were ready to proceed. High-quality headphones (Sennheiser HD 380) were used for stimulus playback. A tone at the start of the trial was delivered through PsychoPy and recorded via the eye tracker's microphone to synchronize the eye tracker and PsychoPy data. Participants listened to all nonwords while focusing on a cross symbol in the center of the laptop screen. They were instructed to press the space bar when they detected the target phenome while keeping their hand on the key throughout the trial.

Participants were individually tested at their respective schools, with each session lasting approximately 90 minutes. Breaks were provided as needed. Consent forms were collected prior to testing. Each session began with the phoneme monitoring task and proceeds with cognitive and other perceptive and rhythmic tasks not included in the present study. Ethical approval for the study was granted by the Ethics Board of the University of Konstanz (IRB statement 05/2021).

### **3.2.1.b Individual Assessment**

Accounting for the variability in the cognitive makeup of individuals with DD (Barbosa et al., 2019; Cheng et al., 2021; Chutko et al., 2022; Gathercole et al., 2006; Gathercole & Baddeley, 1995; Knoop-van Campen et al., 2018; Lallier et al., 2010; Masoura et al., 2021; Menghini et al., 2011; Ramus & Szenkovits, 2008; Valdois, 2022) this study examined working memory and shifting attention along with non-verbal reasoning. Attentional capacity was measured using the NEPSY-II *Response Set* (RS) subtest (Kemp, 2007; Urgesi, 2011), where participants had to listen to a pre-recorded list of words and touch a single colored circle when a certain matching or no-matching color was heard (e.g. “touch the yellow circle when you hear the word red”, cf. Brandt, 1989; Green & Bavelier, 2012). This Stroop-like task assesses the ability to retain and shift attentional focus on complex response sets while inhibiting automatic responses (Kemp, 2007). Working memory was assessed using the *Letter-Number Sequencing* (LNS) subtest from the WISC-IV (Orsini, 2012; Wechsler, 2003) which involved listening to, ordering, and repeating mixed series of letters and numbers that were presented orally. Derived scores from those subtests were transformed into standard scores ( $M = 10$ ,  $SD = 3$ ) based on Italian normative data from Urgesi (2011) for the RS subtest and from Orsini (2012) for the LN subtest.

Given that the working memory capacity and shifting attention may be strongly correlated (Gresch et al., 2024; Narhi-Martinez et al., 2023), a factor analysis was performed using the Promax rotation and Bartlett's method implemented in the R package "psych" (Revelle, 2024). The analysis indicated that one factor was sufficient to capture the covariance across all participants' cognitive measures and age, accounting for 42% of the total variance (SS loadings = 1.70). The factor had the following loadings: *age* (.58), *IQ* (.80), shifting attention (.74) and working memory (-.40), with their uniquenesses being .84, .66, .35 and .45, respectively. Accordingly, shifting attention and working

memory were highly correlated ( $r = .61$ ), while both were moderately correlated with IQ ( $r = .43$  for shifting attention;  $r = .47$  for working memory). Therefore, the cognitive factor score derived from the factor analysis was used in the statistical analysis to account for a proxy of each participant cognitive profile, where more than one cognitive measure was necessary to address the research question.

Table 1 presents descriptive statistics for all individual measures, comparing the two experimental groups.

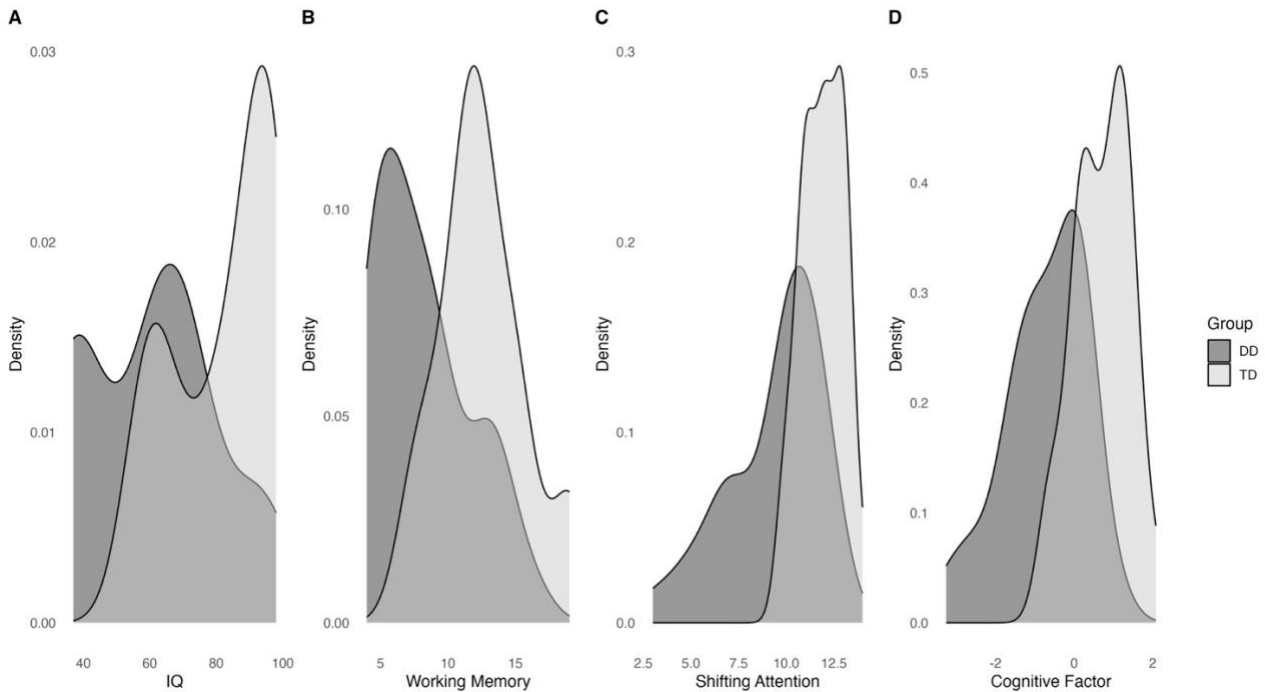
<b>Group</b>	<b><i>Mdn</i></b>	<b><i>M</i></b>	<b>Min</b>	<b>Max</b>
<b><i>IQ</i></b>				
DD vs TD: ( $W = 168.5, p = < .001$ )				
TD	85	60.53 (19.49)	37	94
DD	63	81.86 (15.11)	57	98
<b><i>Shifting attention standard scores (RS)</i></b>				
DD vs TD: ( $W = 127.5, p = < .001$ )				
TD	12	11.9 (1.1)	10	14
DD	10	9.3 (3.4)	3	12
<b><i>Working memory standard scores (LNS)</i></b>				
DD vs TD: ( $W = 151.5, p = < .001$ ),				
TD	12	12.5 (3.2)	7	19
DD	7	8.1 (3.4)	4	16
<b><i>Cognitive factor</i></b>				
DD vs TD: ( $W = 100, p = < .001$ )				
TD	0.74	0.7 (0.7)	-0.63	0.99
DD	-0.58	0.7 (1.02)	-3.25	2.07

**Table 1<sup>5</sup>** Overview of participant scores on cognitive measures comparing the experimental groups (typical development TD, development dyslexia DD) in the present study.

Again, due to the small sample size and non-normal distribution, group-level differences in individual measures were analyzed using the Wilcoxon-Mann-Whitney (WMW) test (Fay & Proschan, 2010; Vierra et al., 2023) in the R package “stats” (RCoreTeam, 2022). Overall, the DD group exhibited significantly lower IQ ( $W = 168.5, p = < .001$ ), working memory ( $W = 151.5, p = <$

<sup>5</sup> Figures and Tables are numbered independently within each study, restarting from Figure 1.

.001), shifting attention capacity ( $W = 127.5, p = < .001$ ) and cognitive factor values ( $W = 100, p = < .001$ ). However, as shown in Figure 1, there was substantial overlap between the two groups across all measures.



**Fig. 1** Density distribution of cognitive measures (Intelligence Quotient (IQ), Working Memory, Shifting Attention, and Cognitive Factor) across the two participant groups. The dark grey distribution shows values measured in the dyslexic group (DD), the light grey distribution shows values of the typically developing participants (TD).

### 3.2.1.c Data Pre-processing and Statistical Analyses

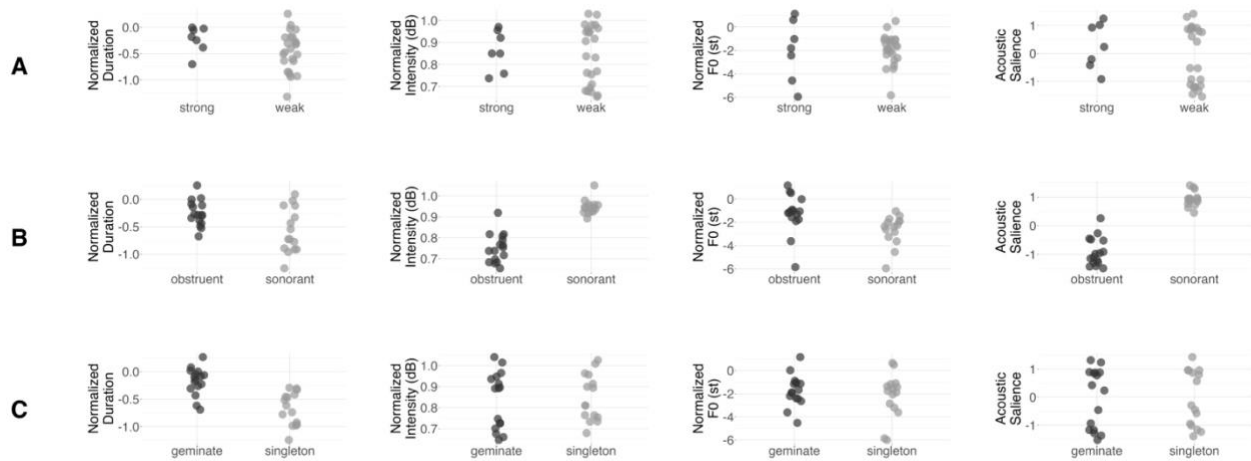
#### a. Acoustic stimuli

To investigate the influence of acoustic factors on the participants while correctly identifying phoneme targets, we extracted target duration (in ms) and intensity (in dB), along with the fundamental frequency F0 (in st) of the vowel target using PRAAT software (Boersma & Weenink, 2007). The extracted acoustic measurements underwent a normalization process, using the average as a baseline (Chu & Feng, 2001). The target duration and intensity were normalized by dividing each value by the average syllable duration and intensity within the item. Duration ratios were log-transformed. Higher positive values indicated an increase relative to the baseline duration (ms) and intensity (dB). The F0 of target vowels was normalized using the semitone conversion formula shown in (1):

$$(2) F0(st) = 12 * \log \left( \frac{f0a/f0b}{\log 2} \right),$$

where  $f0a$  represents the mean frequency across all vowels in the item, and  $f0b$  corresponds to the specific target vowel's frequency. This semitone conversion, frequently applied in music, accounts for the logarithmic perception of pitch by the human auditory system (Mary Zarate et al., 2012). This procedure produced a normalized pitch change metric with values near 0 indicating no pitch change, negative values indicating a pitch decrease, and positive values indicating a pitch increase. The normalized pitch values revealed that only 15% indicated an increase in pitch. This proportion may align with a potential tendency toward an H+L\* pitch accent exhibited by the recorded speaker, a pattern previously identified in earlier research (Rossi & Rathcke, in preparation) and extensively present across Italian varieties (D'Imperio, 2002). To mitigate potential bias in the factor analysis, a single outlier corresponding to the sole sonorant characterized by an H\* pitch accent was excluded. Cross-correlation analysis confirmed a negative moderate correlation between normalized intensity and both normalized F0 and duration (intensity & F0:  $r = -0.36$ ; intensity & duration:  $r = -0.40$ ). Conversely, F0 and duration exhibited a poor correlation ( $r = 0.16$ ).

To test acoustic processing across our participants while accounting for cross-correlations involving acoustic measures (Black et al., 2023; Rathcke et al., 2024), we performed a factor analysis. While normalized intensity was negatively correlated with both normalized F0 and duration, a negligible correlation index was found between the latter two. Inspection of the scree plot and Bartlett's method from the R package “psych” (Revelle, 2024) revealed that one factor was sufficient, accounting for 41% of the total variance (SS loadings = 1.23). The factor had the following loadings: F0 (0.95), intensity (-0.38), and duration (-0.43), with their uniqueness being 0.85, 0.10, and 0.82 respectively. This suggests that the factor accounted more for the variance in intensity compared to the other acoustic measurements. The derived factor was implemented in the data analysis as a proxy for the acoustic salience of the target in the stimulus. Figure 2 compares the distribution of all acoustic measurements of the stimuli across the three linguistic contrasts in the study, i.e. strong (accented)/weak (unaccented), obstruent/sonorant, geminate/singleton.



**Fig. 2** Overview of the acoustic measurements comparing: (A) weak and strong syllables (prominence); (B) obstruents and sonorants (target type); (C) geminates and singletons (gemination).

To further investigate whether, and to what extent, the variance in these distributions could be predicted by the linguistic contrasts present in our stimuli, linear regression analyses were conducted using RStudio (RStudio Team, 2022). The results are presented in Table 2 (RStudio, 2022). Prominence was primarily marked by the intensity of the target consonants themselves, with stronger targets exhibiting higher intensity. Although targets in strong syllables tended to be longer compared to those in weak syllables, this difference remained a trend rather than a statistically significant effect. In contrast, variability in F0 did not systematically contribute to the encoding of prominence. All acoustic measurements contributed to the difference between sonorants and obstruents, with sonorants being shorter and higher in intensity, while their associated vowels exhibited, on average, a comparatively lower F0 relative to the other vowels in the item, compared to obstruents. The key acoustic correlate of gemination was the duration of the consonant targets, with longer consonants being identified as geminate. As a result, sonorants and targets in strong syllables had higher values of acoustic salience compared to obstruents and targets in weak syllables. Although geminates had higher acoustic salience compared to singletons, this difference was not enough to reach significance.

In summary, while target type relied on a combination of acoustic cues, prominence and gemination in this set of stimuli seemed to only be distinguished by unique correlates, respectively, intensity and duration. The F0 of the target vowel appeared to play a specific role in differentiating between obstruent and sonorant targets without influencing the differentiation of the other contrasts. Conversely, duration seemed to act as the most influential correlate across the considered language contrasts.

<b>D. PROMINENCE</b>				
	$\beta$	$t$	$df$	$p$
<i>Duration</i>	-0.15	-1.82	27	.078
<i>Intensity</i>	-0.05	-3.32	27	.002
<i>Pitch</i>	0.23	0.35	27	.72
<i>Acoustic salience</i>	-0.47	-3.24	27	.003
<b>E. TARGET TYPE</b>				
	$\beta$	$t$	$df$	$p$
<i>Duration</i>	-0.33	-4.61	27	<.001
<i>Intensity</i>	0.21	15.02	27	<.001
<i>Pitch</i>	-1.42	-2.60	27	.014
<i>Acoustic salience</i>	1.95	15.98	27	<.001
<b>F. GEMINATION</b>				
	$\beta$	$t$	$df$	$p$
<i>Duration</i>	-0.48	-6.70	27	<.001
<i>Intensity</i>	0.008	0.64	27	.52
<i>Pitch</i>	-0.52	-0.96	27	.34
<i>Acoustic salience</i>	0.16	1.37	27	.17

**Table 2** Summary of best-fit linear regressions examining the role of acoustic cues to: (A) prominence (strong/weak); (B) target type (sonorant/obstruent); (C) gemination (geminate/singleton) in the experimental stimuli.

#### b. Responses

The total number of correct responses (n-hit), missed responses (n-miss), false alarms (n-fa), and correct rejections (n-cr) were extracted from the raw PsychoPy data. Correct responses were initially treated as a proxy for participants' accuracy and coded as 1 to differentiate them from missed or anticipated responses, which were coded as 0. Subsequently, all totals (1 and 0) were input into the  $d'$ -prime function within the *Psycho* R package (Makowski, 2018) to calculate individual  $d'$ -sensitivity for each participant (Macmillan & Creelman, 2004).  $d'$ -sensitivity is an index of a person's ability to distinguish between signal and noise in a detection task (Macmillan & Creelman, 2004). A higher  $d'$ -value indicates better discrimination between targets and distractors, while a lower  $d'$ -value reflects reduced sensitivity.

#### c. Pupillometry

The raw pupillometry data were extracted in the form of a .csv file using Tobii Pro Lab software (v.1.207, TobiiAB, 2022b) and contained average pupil size measurements recorded at 20 ms intervals. The dataset was then temporally synchronized with experimental data from PsychoPy by aligning the synchronization tone presented in PsychoPy with the corresponding recording from the eye tracker's microphone. Missing data were automatically excluded by the recording software before

being saved to the device. Interpolation (Mathôt & Vilotijević, 2023) and the blinks labeling (Fink et al., 2023) were therefore not applicable, though also unnecessary being data modeled using generalized additive mixed models (GAMMs) (Fink et al., 2023). Only trials with no more than 30% missing data were included in the analysis (Korn et al., 2017; Meissner et al., 2024). Following the method described by Mathôt et al. (2018), a subtractive baseline correction of 500 ms was applied before the onset of the target, where present, or before the onset of each nonword for control stimuli. Before statistical testing, the data were down-sampled to intervals of 20 units. The temporal envelope of pupil diameter was then rescaled so that target onset coincided with 0 ms; consequently, negative temporal values corresponded to the time between nonword onset and target onset. Only pupil data related to targets that were correctly identified were considered in the statistical analysis, thus excluding pupil activation related to missing or incorrect targets, i.e., responses occurring before target onsets. Accordingly, only pupil activation in response to the correct rejection of controls, thereby removing false alarms, was included when considering the average pupil dilation while processing control stimuli. This was done to equally compare the pupil activation of the two groups in the process of accurately processing targets and correctly discarding non-targets. On average, the TD group processed correctly approximately 65% of the 32 phoneme target items and 90% of the 32 control items. In contrast, participants in the DD group correctly processed 35% of the 32 phoneme targets and 80% of the 32 control items.

#### d. Statistical analysis

Mixed linear regressions were applied to the  $d'$ -values to assess participants' sensitivity, while accuracy was analyzed using a dataset restricted to correct responses. In this analysis, accuracy served as the dependent variable in logistic mixed-effects regressions, estimated using maximum likelihood (ML) and the BOBYQA optimizer. To investigate the effect of cognitive profile on phonological processing, we examined the interaction between *group* (TD vs. DD) and the *cognitive factor* comprising measures of shifting attention, working memory, and IQ, all age-adjusted across both  $d'$ -sensitivity and accuracy.

The unaggregated nature of the accuracy measure, calculated for each stimulus, allowed for the additional investigation of interaction between *group* and the *acoustic salience*. The interactions between *group* and *gemination* (singleton/geminate), *target type* (obstruent/sonorant), and *prominence*(weak/strong) were included as control interactions to further test the hypothesis of impaired phonological and prosodic representations.

To further examine the impact of *acoustic salience* and *cognitive processing* on phonological processing, generalized additive mixed models (GAMMs) were applied to pupil dilation measures for both target and control stimuli. Subsequently, we investigated

correlations between average pupil dilation within the peak interval and acoustic salience, cognitive resources, and  $d'$  sensitivity.

All analyses were conducted using RStudio, with the following packages: *tidyverse* (Wickham et al., 2019), *lmerTest* (Kuznetsova et al., 2017), *lme4* (Bates et al., 2015), *mgcv* (Wood, 2011), and *corr.test* (R Core Team, 2022). To account for variability across stimuli and participants, both were included as random effect. The maximal random effects structure, including both random intercepts and random slopes, was retained if the regression models converged and did not produce singular fits (Barr et al., 2013). The best-fit regression models were obtained using a backward-fitting procedure. Initially, all interactions of interest were included, and non-significant interactions were subsequently removed stepwise based on the likelihood-ratio test (Bates et al., 2015). In the GAMMs, *group* included as both parametric and smooth terms. K values for smooth terms were determined using the “*gam.check()*” function to ensure appropriate smoothing. The best-fitting GAMMs were identified by comparing the resulting models with a null-based model to assess the significant contribution of group affiliation to pupil variations using the “*compareML()*” function. This was further evaluated in two steps: first, by inspecting the smooth terms using “*plot\_smooth()*”, and second, by analyzing differences in smooth shape across groups using “*plot\_diff()*” (following Wieling, 2018; van Rij et al., 2019; Sósokuthy, 2021). Restricted maximum likelihood (REML) estimation was then selected as the optimal method for fitting the smooth function after comparison.

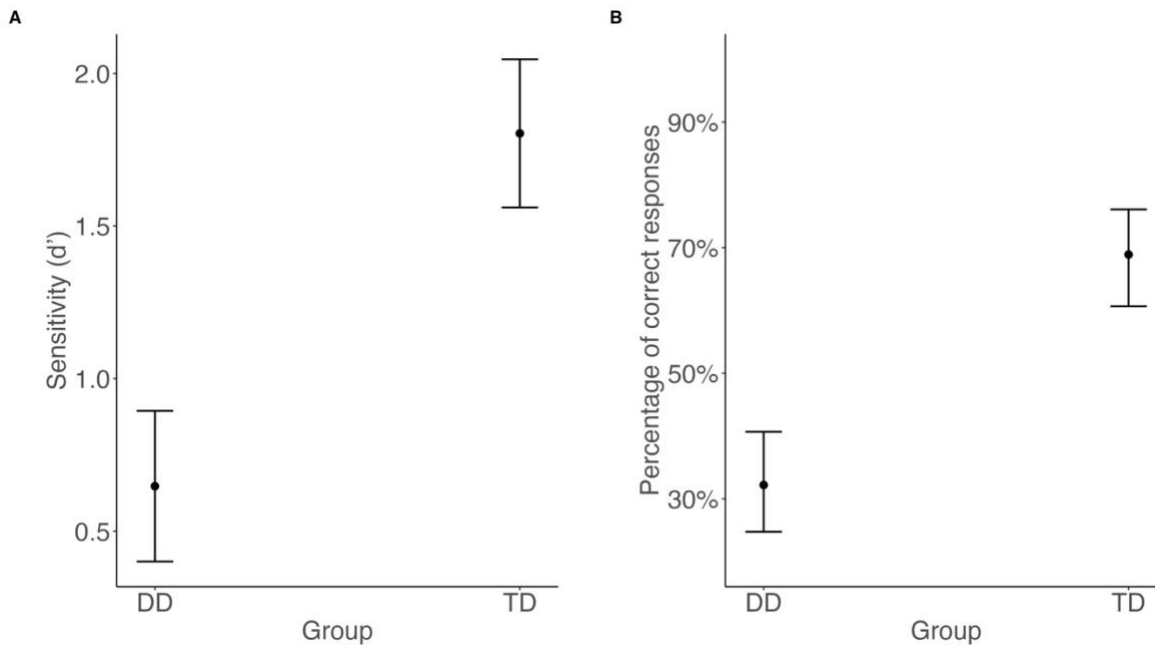
### 3.2.2 Results

#### 3.2.2.a Analysis of $d'$ -Sensitivity and Accuracy

The best-fitting model for  $d'$ -values calculated for each participant revealed a significant main effect of group accounting for 44% of variance ( $F(1,55) = 42.82, p < .001$ ). Cognitive factor was not significant both as interaction ( $F(1,53) = 0.15, p = .69$ ) and main effect ( $F(1,54) = 1.53, p = .22$ ).

Similarly, the best-fitting mixed model for accuracy also reported a sole main effect of group, explaining 31% of the variance ( $\chi^2(1) = 38.54, p < .001$ ). Neither the cognitive factor, nor acoustic salience significantly interacted with group (group\*cognitive factor:  $\chi^2(1) = 1.87, p = 1.71$ ; group\*acoustic salience:  $\chi^2(1) = 0.12, p = .72$ ), nor did they explain variability in accuracy as main effects (cognitive factor:  $\chi^2(1) = 0.63, p = .42$ ; acoustic salience:  $\chi^2(1) = 0.75, p = .38$ ). Accordingly, none of the addressed language contrasts, including prominence (weak/strong), significantly explained the variance in the data, either as an interaction effect, or as main effect (group\*prominence:  $\chi^2(1) = 0.08, p = .77$ ); prominence:  $\chi^2(1) = 3.13, p = .07$ ).

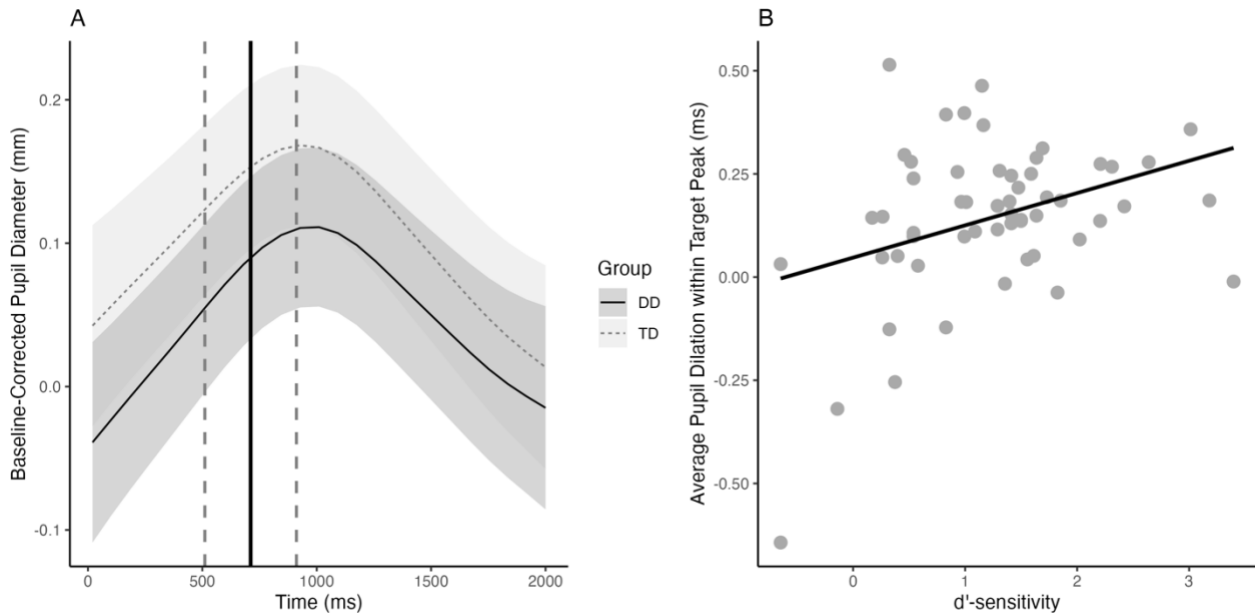
The inspection of plots as presented in Figure 3 confirmed that both models' outcomes were primarily driven by the DD group exhibiting lower sensitivity and accuracy for phoneme targets as compared to the TD group which were not mediated by acoustic salience, nor by cognitive abilities.



**Fig. 3** Estimates of  $d'$ -sensitivity (panel A) and accuracy (panel B) among clinical (DD) and control (TD) participants.

### 3.2.2.b Analysis of Pupillometry

The generalized additive mixed model (GAMM), fitted to correctly identified targets with stimuli and participants included as random effects, did not show group as a significant predictor, either as a parametric term or as a smooth term (parametric:  $\beta = 0.025$ ,  $SE = 0.032$ ,  $t = 0.783$ ,  $p = .434$ ; smooth TD:  $F(0.03,0.04) = 0.15$ ,  $p = .940$ ) Model comparisons using maximum likelihood (ML) demonstrated that the group-based model was not a good fit for the pupil data (AIC difference = -0.05;  $p = .695$ ) Correlation analyses using Pearson's product-moment revealed a significant relationship between  $d'$  sensitivity and the target pupil size variations within the peak window of 927 ms for TD and 1010 ms for DD following target onset ( $r(53) = 0.35$ ,  $p = .008$ ). Figure 4B shows the nature of the positive correlation, highlighting how the higher the pupil dilation, the higher the  $d'$  sensitivity. Neither cognitive factors nor acoustic salience exhibited a significant correlation with target pupil size variations (cognitive factor:  $r(53) = 1.16$ ,  $p = .22$ ; acoustic salience:  $r(53) = 1.22$ ,  $p = .22$ ).

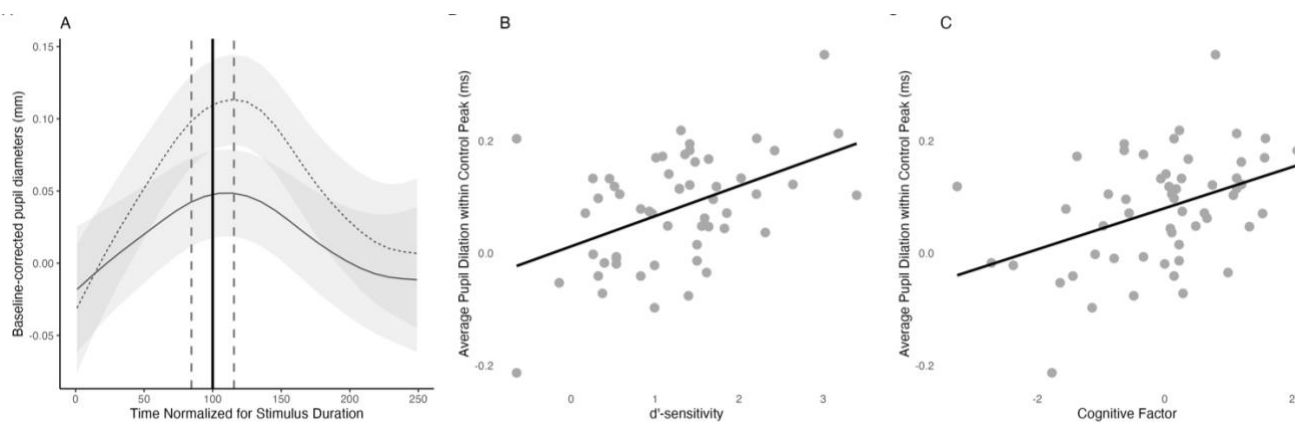


**Fig. 4** A Estimates of baseline-corrected pupil diameters restricted to correctly identified targets. The solid line represents the normalized target end while dotted lines indicate standard deviation. B Correlation between average for individual pupil size in the peak range and sensitivity  $d'$  across participants.

In contrast to pupil size associated with correctly identified targets, the best-fitting GAMM for pupil size restricted to correctly rejected controls revealed a significant main effect of group. (parametric:  $\beta = 0.038$ ,  $SE = 0.015$ ,  $t = 2.417$ ,  $p = .015$ ; smooth TD:  $F(3.914, 4.357) = 5.174$ ,  $p < .001$ ). Model comparison using maximum likelihood (ML) demonstrated that the group-based model was a good fit for the pupil data (AIC difference = 0.21;  $p < .008$ ). Figure 5A shows that this effect is due to individuals with DD exhibiting significantly reduced pupil dilation compared to TD participants.

Again, Pearson's product-moment correlation analyses revealed a significant correlations between  $d'$  sensitivity and pupil size variations in response to control stimuli within the peak window of 1140 ms ( $r(53) = 0.46$ ,  $p < .001$ ). Although distractors did not elicit responses,  $d'$  reflects the ability to correctly distinguish between targets and non-targets, capturing both responses to targets and the ability to withhold responses to distractors. Thus, pupil dilation in this range may reflect cognitive processes linked to signal detection efficiency rather than motor responses alone. For this reason, this analysis was included to examine the broader role of  $d'$  in perceptual decision-making. In addition the correlation with Cognitive Factors, but not with Acoustic Salience, was also significant (Cognitive Factor:  $r(53) = 0.41$ ,  $p = .002$ ); Acoustic salience:  $r(53) = 0.007$ ,  $p = .78$ ). Figures 5b and 5c illustrate the nature of the significant correlations, highlighting a direct proportional relationship between pupil size increase and both  $d'$  sensitivity and individual cognitive profile.

Overall, pupil size variations for both target and control conditions were strongly influenced by  $d'$  sensitivity to phoneme monitoring, while pupil size variations in the control condition alone were mediated by individual cognitive resources.



**Fig. 5** A Estimates of baseline-corrected pupil diameters restricted to correctly rejected controls among clinical (DD) and control (TD) participants normalized for control stimuli duration (the solid line represents the normalized target end (100% = target duration, 150% = total duration + 50%), while dotted lines indicate standard deviation). B Correlation between average for individual pupil size in the peak range and sensitivity  $d'$  across participants. C Correlation between average for individual pupil size in the peak range and cognitive factor across participants

### 3.2.3 Discussion

The aim of the current study was to further investigate the interplay between phonological abilities, prominence sensitivity, and cognitive mediation in Italian children with and without DD. Additionally, by placing more targets in less prominent syllables, the study sought to further examine the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), contributing to a deeper understanding of whether the lexical stress deficit in DD is more related to difficulties in processing phonemes in syllables with higher or potentially lower prominence. Notably, the parallel use of behavioral and more implicit pupillometry measures—sensitive to both phonological and cognitive processing—was implemented to further clarify the link between phonological processing and cognitive resources, thus providing deeper insight into the Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008).

To do so, we compared the performance of 28 children with DD and 29 typically developing peers using a simplified phoneme monitoring task (Bogliotti et al., 2008; Breier et al., 2001; Foss & Gernsbacher, 1983; Foss, 1969; Foss 1973; Rathcke & Lin, 2021; Smith & Rathcke, 2017), adapted from a version previously administered to Italian adolescents described in chapter 2.2. The task required participants to identify geminates versus singletons and obstruents versus sonorants, with targets embedded in strong and weak syllables of non-words. This adaptation ensured comparability with adolescent studies while also accounting for potential differences in auditory sensitivity underlying phonological contrasts. Additionally, we considered individual cognitive profiles, defined

as a combined measure of working memory, shifting attention, and age-adjusted IQ, to examine their influence on performance.

According to the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), we predicted that acoustic salience would mediate group differences in phonological accuracy and sensitivity, correlating with pupil size variations during phoneme monitoring, regardless of orthographic depth. As an alternative explanation, based on the Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008), we hypothesized that differences in accuracy and sensitivity could be mediated by individual cognitive profile, which in turn might be linked to pupil size variations when identifying targets and excluding non-targets in children with DD.

The results first demonstrated that Italian children with DD, similar to Italian adolescents, exhibited significantly lower sensitivity and accuracy in phoneme identification compared to the TD group. This difference was also reflected in normalized pupillometry responses, but only at the level of correctly rejected non-targets. Specifically, when children with DD correctly identified target phonemes, their peak pupil diameter was comparable to that of TD children. However, when correctly detecting non-targets (i.e., withholding a response), their peak pupil diameter was significantly lower. Notably, phoneme sensitivity significantly correlated with normalized average pupil diameter, suggesting that pupil size serves as a reflective marker of phonological identification.

The significant differences in phoneme identification between DD and TD were not mediated by acoustic sensitivity to prominence, as the interaction between group and acoustic salience was non-significant within the accuracy model. Additionally, acoustic salience did not correlate with average normalized pupil diameter, regardless of whether participants were detecting targets or rejecting non-targets. Notably, neither acoustic salience as a significant correlate of prominence nor prominence itself interacted with group while predicting accuracy.

Conversely, similar to the accurate performance observed in adolescents, there was a tendency for targets in prominent syllables to be easier to identify across all participants. However, this remained a statistical trend, likely due to reduced statistical power resulting from the imbalance between targets in weak and strong syllables.

Furthermore, consistent with adolescent data in Section 2.2, there was no evidence of a segmental-level sensitivity deficit, as lower accuracy was observed uniformly across all language contrasts.

Although no behavioral measure, including cognitive factors, could fully explain the significant differences in phoneme identification, the combined cognitive factor significantly correlated with average normalized pupil diameter differences when participants had to ignore non-

targets. This suggests that individual cognitive resources played a role in mediating responses to non-targets. In this regard, children with DD primarily differed from their TD peers in their ability to filter out non-targets. This pattern aligns with the Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008), which posits that phonological difficulties in DD are partly driven by broader cognitive constraints.

Several explanations can be proposed for the group-level differences in pupil response while addressing non-targets. Although still highly debated, target selection and distractor inhibition may not simply represent two outcomes of a single attentional selection mechanism. Instead, they can be considered independent processes, potentially relying on distinct neural substrates (Geng, 2014; Marini et al., 2013; Marini et al., 2016; Noonan et al., 2018; Sabri et al., 2014). In particular, the ability to detect distractors may require an additional inhibitory component (Marini et al., 2013; Noonan et al., 2018). Crucially, inhibition has been found to be impaired in DD and has been linked to the difficulties observed in individuals with DD in quickly refocusing their attention during trials involving continuous stimuli (Doyle et al., 2018; Lallier et al., 2010; Wilcockson et al., 2019). Therefore, specific cognitive impairments and underlying substrates, such as those relying on distractor processing rather than target processing, would effectively explain changes in phoneme access in DD.

Although this is a prominent view, it does not entirely align with the present data, where the percentage of correctly processed distractors in the DD group was much higher than the percentage of correctly processed targets. This means that cognitive resources differed precisely in the process with the best performance. In this regard, Marini et al. (2013) demonstrated that a filtering mechanism is engaged to manage impending distractions, leading to a significant behavioral cost in no-distractor trials during a speeded tactile discrimination task. This finding highlights how the co-occurrence of cost-related processes may interfere with target selection. Similarly, in an ERP study, Sabri et al. (2014) demonstrated that processing irrelevant information places a substantial load on working memory, which, as a consequence, reduces the availability of executive function and attentional resources needed to focus on task goals. Given the multiple and heterogeneous deficits in working memory, executive function, and attentional resources observed in DD (Barbosa et al., 2019; Cheng et al., 2021; Chutko et al., 2022; Gathercole et al., 2006; Gathercole & Baddeley, 1995; Knoop-van Campen et al., 2018; Lallier et al., 2010; Masoura et al., 2021; Menghini et al., 2011; Ramus & Szenkovits, 2008; Valdois, 2022)—as also reflected in our participants—children with DD may quickly exhaust their cognitive resources when processing distractors. This could be due to an increased cost associated with a filtering mechanism, potentially triggered by a reduced working memory capacity. As a result, the remaining cognitive resources in DD may be sufficient for

identifying a limited number of targets but insufficient for processing all targets while simultaneously managing the suppression of non-targets. This limited availability of cognitive resources, in turn, could explain why pupil diameter was comparable between groups for the few identified targets but significantly differed for non-targets. Therefore, the difference in distractor processing may indicate a reduced cognitive substrate available for handling the filtering system which ultimately would affect the target identification process. This explanation is supported by pupillometry studies showing that when cognitive resources, particularly attentional capacity, are reduced—such as in older adults compared to younger individuals—pupil size increases in response to task demands but exhibits a generally smaller overall dilation (Piquado et al., 2010; Tekin et al., 2018; Zhao et al., 2019).

Notably, the correlation between cognitive resources and pupil responses in our findings aligns with previous research indicating that pupil diameter is a reliable marker of cognitive resources availability. (Hoeks & Levelt, 1993; Kolnes et al., 2024; Mathôt, 2018; Pichora-Fuller et al., 2016; Piquado et al., 2010; Robison & Unsworth, 2019; Winn et al., 2015). Furthermore, the consistent correlation between  $d'$  sensitivity and pupil size across both targets and non-targets reinforces the idea that pupil size is also sensitive to phonological processing (Chiossi et al., 2023; Liao et al., 2016; Zarcone et al., 2016). In this context, within DD research, pupil size may serve as an implicit measure to capture the subtle interplay between phonological and cognitive processing.

Overall, the findings of the current study support the Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008) of phonological processing in DD but, once again, do not support the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), as no group-level differences were observed in processing targets as a function of prominence. The results suggest that the interaction of multiple and parallel cognitive domains—rather than the contribution of a single domain—is crucial for accessing phonemes in Italian children with DD, particularly when those phonemes are embedded in an ecological context with competing stimuli. This underscores the necessity of accounting for an individual's cognitive profile when assessing phoneme identification abilities in DD.

### 3.3 Study 4: Acoustic Sensitivity to Lexical Stress in Children

DD is most consistently characterized by phonological speech perception deficits measurable even before the onset of literacy (Melby-Lervåg et al., 2012; Snowling, 1995, 2003). Studies have repeatedly demonstrated that, compared to typically developing listeners, dyslexic listeners have difficulties with perceptual classification and representation of speech sounds. These difficulties become apparent primarily in categorization and discrimination tasks, tapping the ability to process acoustic cues encoding linguistic contrasts (Casini et al., 2018; Masterson et al., 1995; Noordenbos & Serniclaes, 2015; Serniclaes et al., 2001; Vandermosten et al., 2010; Werker & Tees, 1987). Phonological awareness – i.e., the ability to consciously manipulate language sounds – also tends to show atypical patterns in DD (Wagner & Torgesen, 1987). Notably, the acquisition and development of phonology rely on the processing of speech prosody (Bernard & Gervain, 2012; Bonacina et al., 2019; Demuth, 2015; Gervain & Werker, 2013; Lleo & Demuth, 1999; Tierney & Kraus, 2013), which operates at the utterance level and encompasses linguistic representations of pitch, duration, and intensity (Wagner & Watson, 2010). It is therefore not surprising that an originally prosodic deficit may surface as a phonological impairment in DD (Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013).

Prosodic deficits in DD have been demonstrated in several studies, primarily focusing on English, with some evidence also emerging from more transparent languages like Italian. A common characteristic across these studies is the use of tasks that rely on conscious judgment, which involves a strong metacognitive component. For example, the DEEdee task in Leong et al. (2011) required participants to match words (mainly personal names of cartoon characters and similar items) to DEEdee strings that replaced the original syllables while preserving the original stress pattern (e.g., *Harry Potter* would be correctly matched to DEEdeeDEEdee). Similarly, Caccia et al. (2019) presented a task in which participants had to identify the stress position in trisyllabic non-words (e.g., /dididi/, /gugugu/, /tatata/), which were systematically manipulated to vary in the location of a longer, louder, or higher-pitched syllable.

However, several studies have reported less clear-cut group-level differences between DD and typically developing (TD) participants when controlling for or limiting the metalinguistic demands of the tasks, thereby reducing the reliance on conscious access to lexical stress manipulation (Anastasiou & Protopapas, 2014; Barry et al., 2012; Mundy & Carroll, 2013). These findings raise questions about the predictions of the Temporal Sampling Framework (Goswami, 2011), specifically whether lexical stress representations are inherently impaired in DD or if previously observed difficulties are a consequence of experimental designs that place high metalinguistic demands on participants.

To further address the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), the current study builds on previous findings on stress perception in Italian (Caccia et al., 2019) by employing a less metalinguistically demanding paradigm, designed to be suitable for Italian children, unlike those previously used for Italian adolescents. In contrast to the previous study, the task we deployed here involved a forced-choice perceptual categorization of a prosodically manipulated word by matching the perceived word to its correct image (Bertinetto, 1980; Derawi et al., 2022; Lisker & Abramson, 1964; McMurray et al., 2008; Vandermosten et al., 2010). This experimental approach did not necessitate explicit knowledge or manipulation of the concept of lexical stress, thus reducing cognitive load and enabling a direct assessment of the underlying representations of lexical stress and the associated acoustic cues rather than relying on metacognitive tasks (Caccia et al., 2019; Goswami, Mead, et al., 2013) or correlations across a metalinguistic and a non-linguistic task performance (Leong & Goswami, 2013; Leong et al., 2011).

Within the framework of the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), we predicted a greater level of uncertainty in stimulus categorization, as indicated by a flatter slope of the identification curve (Maassen et al., 2001; Vandermosten et al., 2010) and slower reaction times (Nicolson & Fawcett, 1994; Whelan, 2008). Given that listeners tend to develop categorization during a repetitive task and show a learning effect (Benndorf et al., 2014; Mendonça et al., 2020; Thomas & König, 2018), we further hypothesized a milder learning effect in listeners with DD as compared to typically developing listeners.

### **3.3.1 Method**

#### **3.3.1.a Experimental Procedure**

A forced-choice identification task was created for the purpose of the present study. It involved perceptual identification of five 7-step continua which were created such that their ends represented either a trochaic word (*papa* /'papa/, meaning "pope") or an iambic word (*papà* /pa'pa/, meaning "dad"). The baseline stimulus and the starting point of all continua was a disyllabic non-word, formed by repeating the accented syllable of the word *papa* twice. The word was produced and recorded by a native female speaker of Italian (the first author). The F0 contour of this resulting nonword was flat, with identical duration and intensity resulting in an ambiguous stress placement. The non-word formed the midpoint of all continua.

Four acoustic-prosodic features of the baseline stimulus were manipulated: (1) duration (in ms), (2) intensity (in dB), (3) fundamental frequency, F0 (in semitones), and (4) amplitude rise-time

(in ms). The first three manipulations were carried out using PRAAT (Boersma, 2001) while rise-time manipulations were performed using Audacity 2.0.0 (AudacityTeam, 2014).

The manipulations were located either in the first or in the second syllable of the baseline stimulus. Accordingly, the duration of either the first or the second syllable was gradually reduced by 15%, 30%, or 45% of the original duration, resulting in six duration-manipulated stimuli. The intensity of the first or the second syllable was progressively increased by 3, 6, or 9 dB, leading to six intensity-manipulated stimuli. The original F0-contour of either the first or the second syllable was successively raised by 1, 2, or 3 semitones, resulting in six F0-manipulated stimuli. Finally, the original amplitude rise-time of either the first or the second syllable was shortened by 25%, 50%, or 75%. These manipulation steps were chosen upon informal piloting with native adult speakers of Italian, to achieve a slight but perceivable change in the acoustic-prosodic parameters at each continuum step. In addition, one continuum implemented a combination of all four parameters with the same magnitude and continuum steps as isolated manipulations. That is, progressively increasing F0 and intensity of the first syllable and decreasing duration and rise-time of the second syllable or conversely, progressively decreasing F0 and intensity of the first syllable while concomitantly increasing duration and rise-time of the second syllable. This procedure created five continua in total, with the first three steps of each continuum being more representative of the trochaic word /'papa/, the last three steps being more representative of the iambic word /pa'pa/, and continuum step 4 being the ambiguous baseline stimulus.

Participants listened to a total of 35 stimuli (7 steps \* 5 continua), played back to them via high-quality headphones (Sennheiser HD 380) in a random order using PsychoPy (Peirce et al., 2019). Participants were asked to decide if the stimulus they heard sounded like *papa* (pope) or *papà* (dad) and to click on the respective image presented on the experimental computer screen (MacBook Air with a retina display, 13-inch, 2018) by using the touchpad of the computer. Prior to the start, the experimenter explained the task to each participant individually, showing them the two images and answering any questions. Participants had a chance to familiarize themselves with the task by clicking on images of *gomma* (rubber) or *matita* (pencil) upon hearing the corresponding words.

Participants were individually tested at their respective schools, with each session lasting approximately 90 minutes due to the inclusion of additional experimental activities not discussed here. The task of the present study was performed within 10 minutes. Breaks were taken as necessary. Written consent was obtained from participants' parents or guardians prior to the experiment. The study received ethical approval from the Ethics Board of the University of Konstanz (IRB Statement 05/2021).

### 3.3.1.b Data Pre-processing and Statistical Analyses

Collected responses were extracted from PsychoPy and coded as 1 for the trochaic response *papa* and 0 for the iambic response *papà*. Missing values (10% of all responses) were not included in the analyses. Binomial mixed-effects regressions were conducted using RStudio (2022) and the lme4 package (Bates et al., 2015) with a logistic link function (Jaeger, 2008). The model tested for a three-way interaction between *group* (DD vs. TD), *continuum step* (1-7), and *acoustic correlate* (duration, intensity, pitch, rise-time, combined). *Participant* was included as a random effect. Given the higher power requirements for detecting a three-way interaction (Cotter et al., 2023), a post-hoc power simulation was conducted using the R-package *simr* (Green & MacLeod, 2016) to evaluate the ability of the model to detect a significant effect.

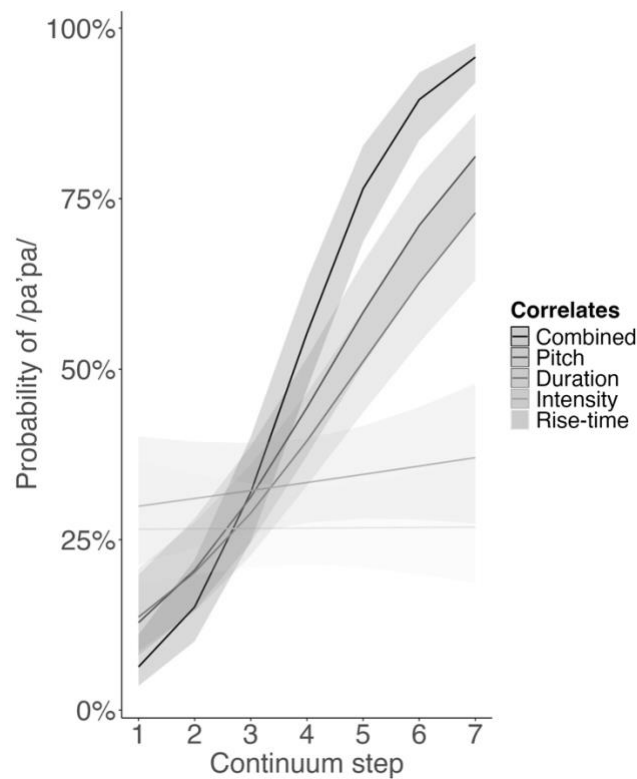
Reaction times (RTs) were also extracted from PsychoPy. RTs measured the speed of a response once a stimulus was heard. To examine group-level differences in reacting to stimuli, we analyzed RTs by fitting a Linear Mixed-Effects Models (Bates et al., 2015) to all RTs measured during the experiment. Again, we tested for an interaction between *group* (DD vs. TD) and *acoustic correlate* (duration, intensity, pitch, rise-time, combined). To further determine potential learning effects during the experiment, we fitted Generalized Additive Mixed Models (GAMMs) from the R-package *mgcv* (Wood, 2011) to RTs measured from the binning until the end of the experiment. The model included *group* as a parametric predictor and *trial order* (i.e., serial order of trials from the first until the last trial) as a smooth term. Separate smooths were estimated for each group. *Participant* was included as a random smooth to account for individual variation in response to *time*. The degree of smoothness was assessed using the `gam.check()` function. Model fit was assessed using the `CompareML()` function (Sóskuthy, 2021) which performs model comparisons based on maximal likelihood. Once the optimal model was selected, the effects were examined using the `plot_difference()` function (Wieling, 2018) which displays the magnitude of time-locked differences between the smooths.

### 3.3.2 Results

#### 3.3.2.a Analysis of Identification Responses

The best-fitting model of response retained a significant interaction between continuum step and acoustic correlate ( $\chi^2 = 128.28$ ,  $p < .001$ ). Figure 1 illustrates the nature of this interaction, demonstrating that participants primarily relied on combined cues, followed by pitch and duration, to categorize "papa" (0) and "papà" (1). In contrast, rise-time and intensity did not serve as reliable

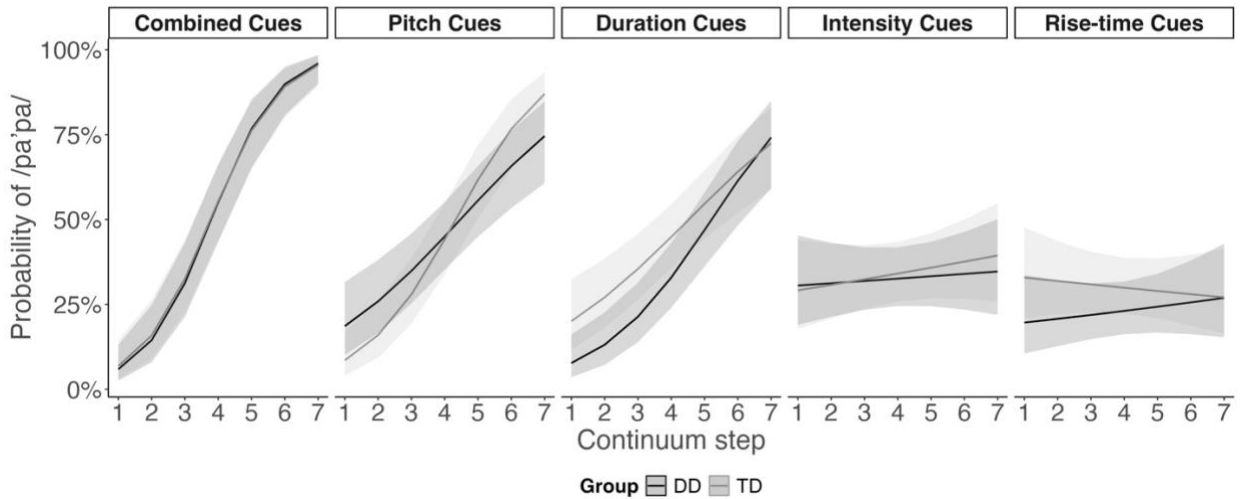
acoustic cues to lexical stress, with participants' categorization ability being below the chance level (50%) and accompanied by relatively large confidence intervals.



**Fig. 1** Predicted<sup>6</sup> probabilities of responding "papà" along the 7-step continuum of the five acoustic correlates tested. The curves represent psychometric identification functions obtained for combined cues, pitch-only, duration-only, intensity-only, vs. rise-time-only cues.

The predicted three-way interaction of *group*, *continuum step* and *acoustic correlate* did not help to significantly improve the model fit ( $\chi^2 = 7.46, p = .11$ ), indicating that the two experimental groups did not significantly differ in their responses to the continua. As shown in Figure 2, the probability of responding "papà" revealed comparable psychometric functions for the two groups in all conditions.

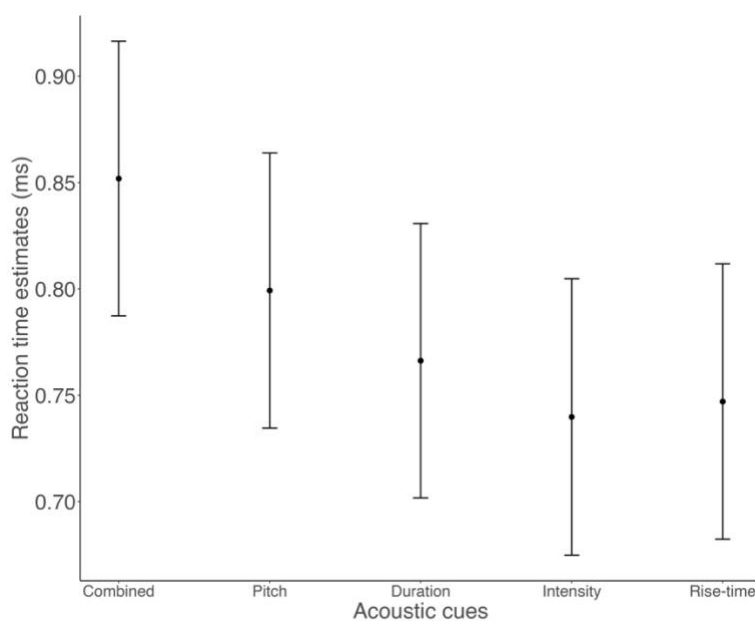
<sup>6</sup> Figures and Tables are numbered independently within each study, restarting from Figure 1.



**Fig. 2** Predicted probabilities of "papà" responses along the 7-step continuum comparing the identification performance of the dyslexic group (DD, black line) and the typically developing group (TD, grey line) on the five acoustic continua of the present study (combined cues, pitch cues, duration cues, intensity cues, and rise-time cues).

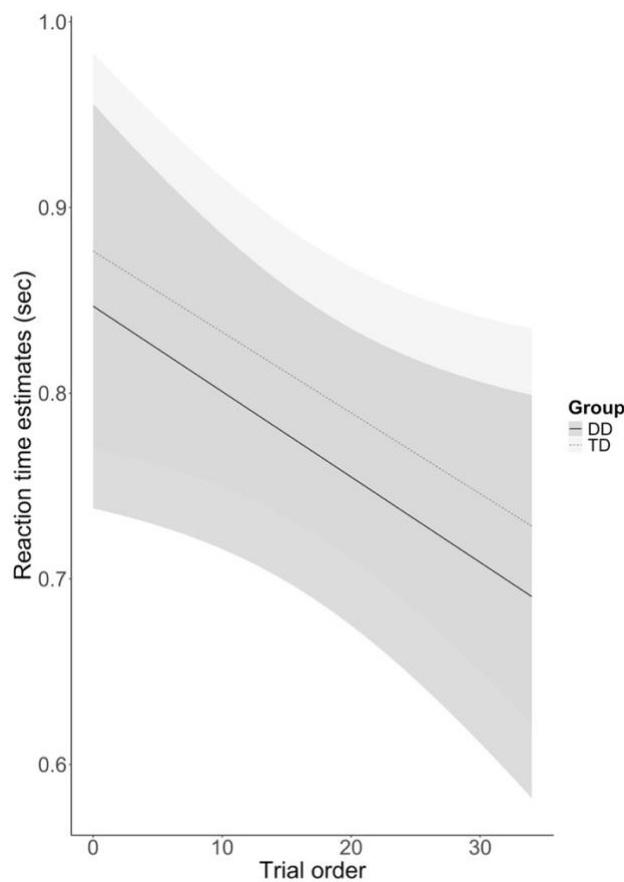
### 3.3.2.b Analysis of Reaction Times

The best-fitting model of reaction times retained a main effect of *acoustic correlate* only ( $F(1, 54) = 0.33, p < .001$ ). Figure 3 illustrates this effect, showing that participants showed slightly longer reaction times for those acoustic correlates that they found meaningful (i.e., combined cues, pitch- and duration-only cues). In contrast, neither the interaction between *acoustic correlate* and *group* ( $F(4, 1698) = 1.45, p = .22$ ) nor the main effect of *group* ( $F(1, 54) = 0.34, p = .56$ ) helped to improve the model fit, indicating that both groups had comparable response times to all stimuli.



**Fig. 3** Reaction time estimates for stimuli with different *acoustic correlates* to lexical stress

The best-fit GAMM of RT changes throughout the experiment did not retain *group* as a significant predictor, either as a parametric term ( $\beta = 0.032$ ,  $SE = 0.05$ ,  $t = 0.59$ ,  $p = .55$ ) or as a smooth term ( $F = 0.04$ ,  $p = .55$ ) while *trial order*, modeled as a smooth term, was a significant predictor in the model ( $AIC = 0.80$ ;  $F = 5.01$ ,  $p = .02$ ). As illustrated in Figure 4, the effect reflects a general tendency to respond faster to each trial as the experiment progressed, indicative of a general learning trend during the task (Benndorf et al., 2014; Mendonça et al., 2020; Thomas & König, 2018). This effect equally held for both experimental groups, suggesting that potential task learning effects were comparable for all participants, no matter their group affiliation.



**Fig. 4** Estimated changes in reaction times across experimental trials, comparing the dyslexic group (DD, black line) and the typically developing group (TD, grey line).

### 3.3.3 Discussion

The present study addressed the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013) by examining lexical stress perception in Italian children, both with and without a formal diagnosis of DD using a real-word identification task. This study aimed to contribute to the ongoing debate regarding the nature of prosodic deficits in DD—specifically, whether these difficulties arise from intrinsically impaired lexical stress representations

or from challenges in accessing them (Anastasiou & Protopapas, 2014; Barry et al., 2012; Mundy & Carroll, 2013).

We tested a total of 27 children with DD and 28 age-matched children with typical development. The task involved categorizing prosodically manipulated 7-step speech continua as either *papa* (meaning “pope”) or *papà* (meaning “dad”, cf. Bertinetto, 1980) by selecting the corresponding image on the screen. By tasking children with matching words to their images, the present study minimized cognitive load of maintaining an auditory impression of a polysyllabic non-word and avoided metacognitive reflections on lexical stress, thus enabling a more direct assessment of perceptual links between acoustic cues and underlying phonological representations. All relevant acoustic-prosodic cues (including pitch, duration, rise time, intensity, and their combination) were systematically manipulated and tested.

Analyses of identification responses and reaction times revealed comparable performance across the two experimental groups, indicating that both DD and TD children were equally sensitive to the presence of acoustic-prosodic cues marking lexical stress and could efficiently make use of them when accessing correct phonological representations. Moreover, learning effects, reflected in faster reaction times as the experiment progressed, were observed in both groups. These findings do not lend support to the hypothesis of perceptual deficits in processing acoustic-prosodic cues and related phonological impairments of representing lexical stress in DD (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013). Specifically, the present results cast doubts on the core idea of the Temporal Sampling Framework (Goswami, 2011) that the perception of lexical stress crucially hinges on an adequate encoding of rise-times in amplitude envelopes of stressed vs. unstressed syllables, given that participants performed below the chance level on those stimuli that manipulated rise-time durations at syllable onsets. This result indicates that amplitude rise-times do not encode lexical stress, at least not in Italian and therefore not universally the Temporal Sampling Framework seems to suggest.

The present findings do not align with previous studies investigating the perception of lexical stress in Italian by means of polysyllabic non-words (Caccia & Lorusso, 2020; Caccia et al., 2019). The key point distinguishing the forced-choice identification task of the present study from the task deployed by Caccia et al. (2019) is the involvement of a metalinguistic ability to reflect on the phenomenon of lexical stress and to deploy the concept in an explicit perceptual judgment of non-words. Strictly speaking, the task taps the perception of acoustic prominence rather than lexical stress perception proper since by definition, non-words do not have a corresponding entry in the mental lexicon (Ladd & Arvaniti, 2023). As recently discussed in a large-scale meta-analysis of prosodic skills in DD, the metacognitive ability to reflect on the form and function of speech prosody is one

part of prosodic competence that may develop later in life and is unrelated to the perceptual ability to adequately use speech prosody for real-world communicative purposes (Mundy and Wood (2024). Phonological representations of lexical stress as well as auditory perception of acoustic-prosodic cues are likely to be intact in DD, but they cannot be not accessed by means of a metalinguistic task (Mundy & Wood, 2024). While Mundy and Wood (2024) propose that the development of conscious, explicit, metalinguistic access to speech prosody may result from an extensive reading experience and that dyslexic difficulties in the metacognitive access to lexical stress arises due to a limited exposure to reading, the cognitive accounts of phonological deficits in DD (Lallier et al., 2010; Ramus & Szenkovits, 2008) cannot be completely discarded as a potential contributor to the previously observed prosodic challenges in DD (Caccia & Lorusso, 2020; Caccia et al., 2019) and should be addressed in future research.

One finding the present study converges on with the results by Caccia et al. (2019) is the main acoustic-prosodic cue for lexical stress. In contrast to earlier research which suggested primarily duration as the main acoustic cue encoding lexical stress in Italian (Bertinetto, 1980; Ferrero, 1972), the present findings as well as Caccia et al.'s results identify F0 as the most reliable, isolated cue of Italian stress, followed (but not superseded) by duration. Given that Italian has little de-accentuation, lexical stress and phrase-level accents usually coincide (Avesani & Vayra, 2005; Leben, 1998), potentially leading to a perceptual shift in cue salience (MacLeod, 2015). Follow-up studies with Italian adult speakers of the same varieties of Italian are needed to confirm that there is indeed a general – rather than purely developmental and therefore potentially temporary – shift in lexical stress encoding in Italian. Alternatively, the observed alignment between lexical stress and phrase-level prominence may result from the use of isolated words as stimuli. Therefore, further research should examine the perception of Italian lexical stress cues within sentence contexts to better understand their role in natural speech processing. Acoustic-prosodic cues identified for Italian stress clearly differ from those of English (Guo, 2022; Mousikou et al., 2024; Plag et al., 2011), highlighting the need for more extensive cross-linguistic research into the role of language-specific acoustic-prosodic encoding and its role in potential prosodic deficits in DD (Caccia et al., 2019; Goswami, Mead, et al., 2013; Leong et al., 2011). The present results raise questions about the cross-linguistic applicability of the idea that DD is linked to an impaired sensitivity to acoustic salience encoding lexical stress, no matter the language of a dyslexic individual.

Taken together, the results of the present study do not support the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013) in Italian-speaking children with DD. Instead, likewise our findings on segmental difficulties in DD, the findings suggest that previously observed deficits (Caccia & Lorusso, 2020; Caccia et al., 2019) might

reflect difficulties in accessing intact representations (Ramus & Szenkovits, 2008), particularly in tasks with higher cognitive demands due to metalinguistic nature of a task (Lallier et al., 2010; Ramus & Szenkovits, 2008). Future cross-linguistic research combining different types of prosodic phenomena and cognitive tasks could provide further insights into the nature of these difficulties, possibly expanding the *Cognitive Mediation Hypothesis* (Lallier et al., 2010; Ramus & Szenkovits, 2008) at the prosodic level. The results further highlight that empirical study of speech prosody ought to be sensitive to the multi-component nature of prosodic competence (Wade-Woolley et al., 2021).

## 4. General Discussion

### 4.1 Synthesis of Background, Methods, and Results

Reading is fundamental for academic success, employment, and access to essential services (Levin-Zamir & Bertschi, 2018; Smith-Spark et al., 2023; Tops et al., 2021). The acquisition of adequate orthographic representations depends on the integrity of various linguistic, sensory, and cognitive domains (Al Dahhan et al., 2016; Ardila et al., 2010; Bryant & Bradley, 1983; Chiappe et al., 2001; Cotton & Crewther, 2009). DD is a clinical condition that negatively impacts the correct acquisition and development of these representations, making it a key factor in understanding the complex architecture underlying the connection between spoken and written representations and their relationship to sensory and cognitive domains (American Psychiatric Association, 2022; Andresen & Monsrud, 2022; Cornoldi & Tressoldi, 2014; Harrison et al., 2021; Sadusky et al., 2022). The complex heterogeneity of the DD phenotype has led to the development of multifactorial models to account for this variability and address the debate surrounding the etiology of the disorder (Potier Watkins et al., 2023; Wolf et al., 2024; Ziegler et al., 2020). However, the developmental trajectories and probabilistic interactions of core deficits in DD remain highly debated, representing an important theoretical and clinical gap.

The present thesis was specifically designed to investigate the interplay between two of those core deficits, namely the impairments in segmental phonological representations (i.e., phonemes), and in lexical stress sensitivity in both adolescents and children with and without DD under the consideration of individually available cognitive resource. Lexical stress sensitivity was specifically investigated through its key features, namely acoustic sensitivity to prosodically marked prominent syllables and to acoustic salience within a lexical context. In doing so, it examined whether the ability to process lexical stress is impaired in Italian DD, disrupting the formation of segmental representations and hindering access to them, as predicted by the Temporal Sampling Framework (Goswami, 2011). Alternatively, in alignment with previous proposal of Ramus and Szenkovits (2008) and further corroborated by existing research (Lallier et al., 2010), we asked whether the phonological deficit could primarily stem from external cognitive computations that restrict access to otherwise intact segmental representations. Given the limited and inconsistent findings regarding lexical stress impairments in DD across transparent languages (Mundy & Wood, 2024), and the greater potential for DD compensation in such orthographies (Ziegler et al., 2010), two distinct age groups—children and adolescents—were compared within Italian as the experimental language. This was done to further examine whether, and how, language-specific properties, particularly

orthographic transparency, shape the nature and detectability of phonological and lexical stress deficits in individuals with DD. Additionally, Italian provided the advantage of duration cues serving as correlates at both segmental and prosodic levels, allowing for a simultaneous and controlled assessment of sensitivity across both linguistic levels.

Therefore, 40 adolescents with DD and 30 adolescents with typical development completed a Phoneme Monitoring Task, as part of Study 1 presented in Section 2.2. In this task, participants identified phonemes embedded in strong and weak syllables of trisyllabic nonwords such as [*segora* 'minu] and [*bipoza* 'viba] (Bogliotti et al., 2008; Breier et al., 2001; Foss & Gernsbacher, 1983; Foss, 1969; Foss 1973; Rathcke & Lin, 2021; Smith & Rathcke, 2017). This was followed by a Sensorimotor Synchronization Task, part of Study 2 presented in Section 2.3, which required participants to tap along with what they perceived to be the beat of spoken Italian sentences (Rathcke & Lin, 2021). In addition, 28 children with DD and 29 children without DD completed a simplified version of the Phoneme Monitoring Task, as part of Study 3 presented in Section 3.2, before engaging in a Categorical Perception Task, conducted in Study 4 and described in Section 3.3. In this latter task, children judged which of two Italian minimal pairs differing in stress placement—such as *papa* ['papa] (“pope”) and *papà* [pa'pa] (“dad”)—best matched a given target stimulus along a lexical stress continuum. Within both age cohorts, the phoneme monitoring task was used to examine how implicit acoustic sensitivity to syllabic prominence relates to phoneme identification, under the consideration of individual cognitive profiles. The subsequent tasks were selected for their reduced metacognitive demands to assess sensitivity to acoustic salience within lexical contexts, with task complexity carefully adjusted to each age group to ensure developmental appropriateness. All participants also underwent a comprehensive cognitive assessment.

Within the framework of the Lexical Stress Sensitivity Hypothesis, which posits that phonological impairments in DD are representational in nature and originate from reduced sensitivity to lexical stress (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), we predicted that individuals with DD would exhibit reduced sensitivity to syllabic prominence in nonwords and lexical stress in words and sentences. Furthermore, the reduced acoustic sensitivity to prominence was expected to extend to the segmental level thus impacting the adequate processing of singleton/geminate and obstruent/sonorant contrasts (Casini et al., 2018; Masterson et al., 1995; Tallal, 1980; Vandermosten et al., 2010). The Cognitive Mediation Hypothesis served as the alternative hypothesis, assuming that group differences do not stem from impaired phonological representations themselves, but rather from restricted access to them, possibly due to the inadequate mediation of co-occurring cognitive deficits (Lallier et al., 2010; Ramus & Szenkovits, 2008).

The analysis of the current findings primarily revealed that phonological identification in Italian adolescents and children is considerably impaired in individuals with DD, as confirmed by the significant group-level differences observed in both children and adolescents on the phoneme monitoring task administered in Study 1 (Section 2.2) and Study 3 (Section 3.2). However, contrary to the predictions of the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), group-level differences in phonological identification did not appear to stem from inherently fragile representations of lexical stress. This conclusion is supported by evidence showing that, first, lower identification rates in phoneme monitoring were homogenous across all phonological contrasts within the DD population, regardless of age. Secondly, the processing of acoustic cues underlying these phonological contrasts was comparable between individuals with DD and their age-matched counterpart across both adolescent and child cohorts.

Further challenging the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013) acoustic sensitivity to lexical stress and prominence was similar between DD and TD groups. This was demonstrated by comparable alignment to weak and strong syllables in spoken sentences among adolescents, as observed in Study 2 (Section 2.3); equivalent categorical perception curves underlying lexical stress among children, as shown in Study 4 (Section 3.3); and similar perceptual advantages of prominence in phoneme identification across both groups, regardless of age, as found in Study 1 (Section 2.2) and Study 3 (Section 3.2). Consequently, the current evidence confirms that acoustic sensitivity to prosodic cues underlying prominence and lexical stress is adequate in both adolescents and children, with and without DD, and does not explain group-level differences in phonological processing among our participants across ages. This finding deviates from the Temporal Sampling Framework (Goswami, 2011), which considers reduced sensitivity to lexical stress representations as a key underlying factor in phonological deficits in DD, thus challenging rather than confirming the Lexical Stress Sensitivity Hypothesis (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013). Conversely, in alignment with the Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008), phonological identification differences between DD and TD, regardless of age, appear to be mediated by cognitive resources. This is primarily supported by evidence from Study 1 (Chapter 2.2), showing that in TD adolescents, high phonological identification rates were observed when attention-shifting levels were high, whereas identification rates were low when attention-shifting scores were low. However, this pattern was not apparent in DD, where performance remained consistently low regardless of shifting attention levels. Secondly, findings from Study 3 (Section 3.2) demonstrated that cognitive abilities mediated group-level differences in pupillometry during

distractor processing in the phoneme monitoring task. These two main findings suggest that cognitive deficits in DD may hinder access to phonological representations that are otherwise intact.

#### **4.2 Age-Based Analysis of Phoneme Identification Performance**

The finding of group-level differences in phoneme identification among both adolescents and children aligns with previous research identifying phonological processing as one of the most consistent deficits in DD (Ramus et al., 2013; Snowling, 2003; Vellutino et al., 2004). In this regard, the magnitude of phonological identification difficulties within the findings current studies remained stable between late childhood and adolescence ( $M d'$ -prime for children = 0.64;  $M d'$ -prime for adolescents = 0.64). This further suggests that phonological deficits in Italian DD, regardless of its higher transparency, are less susceptible to modifications or compensatory trends as reported for other deficits in DD (Danelli et al., 2017; Eloranta et al., 2019; Heim et al., 2008; Menghini et al., 2010; Snowling, 2003), and in disagreement with those who proposed that the phonological awareness deficit diminishes while learning a transparent language (Jong & Leij, 2003). This further corroborates the more cognitive nature of the deficit, which does not seem to involve phonological representations per se and is, for this reason, less affected by the transparency of the language. In addition, those phonological deficits emerged as comparable between adolescents with isolated and comorbid dyslexia, as confirmed by the absence of significant group differences between the two clinical subgroups in the phoneme monitoring task. This further aligns with previous findings suggesting that comorbid learning disorders share the same phonological and most probably linguistic profile (Vellutino et al., 2004).

Although phoneme identification rates were largely comparable between clinical and non-clinical groups in both children and adolescents, some developmental differences did emerge between the two age groups. For instance, unlike adolescents, children aged 8 to 10 years (both TD and DD) did not exhibit a clear processing advantage for gemination or for obstruents, although obstruents were generally—but not significantly—easier to identify than sonorants. The lack of a perceptual advantage for gemination suggests that Italian children still exhibit a non-adult-like and possibly less efficient processing of gemination overall. This is also reflected in the reduced effect of what Dmitrieva (2014) referred to as the acoustic similarity principle across child participants—that is, the smaller the difference in sonority between geminates and the surrounding vowels, the lower the perceptual salience of geminates. In the conducted studies. 1 and 3, this implies that obstruent geminates should have been easier to identify than sonorant geminates, provided that participants could accurately detect geminates and effectively distinguish them from singletons. This, in turn, might have enhanced the significant role of obstruents over sonorants in facilitating phoneme

identification. Since this was observed in adolescent participants but not in children, it is reasonable to assume that the inefficient use of this acoustic similarity principle during gemination processing in our child participants may have also led to a reduced reliance on the obstruent/sonorant contrast, rendering it non-significant. This, in turn, would further suggest a non-adult-like ability to efficiently use the gemination/singleton contrast to facilitate access to phoneme monitoring. This is of particular relevance given that developmental trajectories surrounding the acquisition and manipulation of gemination and are still poorly understood.

### **4.3 Age-Based Analysis of the ability to process Lexical Stress and Prominence**

Beyond developmental differences observed at the segmental level, the studies of the current thesis also confirmed differences in lexical stress processing. In particular, although all participants in studies 1 and 3 identified phonemes more accurately when embedded in prominent syllables, this interaction did not reach statistical significance in children. This suggests that although children can correctly process acoustic cues encoding lexical stress contrasts, their ability to integrate this information with segmental-level processing to enhance phonological identification remains non-adult-like and less efficient compared to Italian adolescents. This finding aligns with Caccia et al. (2019), who reported that the dominance of specific acoustic cues underlying Italian lexical stress is stronger and more consistent in adults than in children. This further supports the hypothesis that lexical stress processing undergoes progressive refinement from late childhood into adolescence (Arciuli & Ballard, 2017; Quam & Swingley, 2014) while following an independent trajectory compared to that of segmental contrasts (Giraud & Poeppel, 2012; Schild et al., 2014). In addition, these findings highlight and possibly expand the notion of multicomponential prosodic competence, distinguishing among its core abilities: acoustic sensitivity and the ability to implicitly use acoustic sensitivity to efficiently sustain access to phonology. Furthermore, the present thesis aligns with Caccia et al. (2019) in identifying in pitch the primary acoustic-prosodic cues for lexical stress in Italian. While earlier research (Bertinetto, 1980; Ferrero, 1972) emphasized duration as the most significant factor in encoding lexical stress, the current findings suggest that both pitch and duration contribute to lexical stress perception in Italian, with pitch playing a more prominent role.

### **4.4 Beyond Acoustic Sensitivity in DD: Rethinking the Lexical Stress Deficit**

The lack of a deficient acoustic sensitivity across both segmental and lexical stress contrasts across the studies of the current thesis deviates from previous research supporting impaired discrimination and categorization of phonological contrasts in DD (Casini et al., 2018; Masterson et al., 1995; Tallal, 1980; Vandermosten et al., 2010), as well as deficits in lexical stress sensitivity

(Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013). Several possible explanations can be considered for this discrepancy. Regarding the segmental level, one possible way to reconcile this discrepancy is by considering that while some deviations in processing acoustic cues encoding segmental contrasts might be present in DD, in more ecological contexts—such as natural speech, where multiple factors contribute to accurate encoding—these deviations have a reduced impact on overall variance (Blomert & Mitterer, 2004; Protopapas, 2014). As a result, they fail to account for phonological identification difficulties in spoken speech.

With regard to lexical stress, an important consideration discussed in Section 1.4 is that evidence for reduced sensitivity to acoustic cues related to lexical stress or prominence in DD has heavily relied on perceptual judgment tasks requiring the conscious manipulation and metalinguistic awareness of stress. These tasks introduce a stronger metalinguistic component in their assessment compared to the one employed in the current studies (Caccia & Lorusso, 2020). As recently discussed by Mundy and Wood (2024) in their meta-analysis, the metacognitive ability to reflect on the form and function of speech prosody is one part of prosodic competence that may develop later in life and is a distinct domain compared to the one related to the adequate encoding of lexical stress representation (Mundy & Wood, 2024). Consequently, it is conceivable that lexical stress representation, as well as the ability to process its underlying acoustic-prosodic cues, is likely to be intact in DD, as suggested by the findings of the current thesis. Nevertheless, in agreement with previous research, it is conceivable that individuals with DD cannot access these representations via a metalinguistic task (Mundy & Wood, 2024). This finding aligns once again with the notion of prosodic competence proposed by Wade-Woolley et al. (2021), where acoustic sensitivity is a distinct but not sole constituent of this competence, which is shared with other components, including prosodic awareness.

In support of this view, our adolescent participants exhibited a significantly faster sustained motor tempo SMT compared to their age-matched counterparts, and we reported how individual differences in SMT contribute to accurate alignment with vowels embedded in weak or strong syllables in our SMS study. Notably, previous findings have reported how SMT is sensitive to IQ variations (Ladányi et al., 2023) and how its rates are reflective of rates in the range of delta neural oscillations (Gunasekaran et al., 2023; Rossi et al., 2024), which are implicated not only in the encoding of stress (Goswami, 2011) but also in attentional resources (Harmony, 2013; Harmony et al., 1996). Consequently, as discussed in Section 2.3, SMT could potentially serve as a marker, possibly indicating how efficiently cognitive resources can be allocated to rhythmic estimation during delta activity. Although this still needs to be tested empirically, it suggests that the challenges reported in the DD literature regarding lexical stress access might indeed be mediated by cognitive resources.

While Mundy and Wood (2024) propose that the development of conscious, explicit, metalinguistic access to speech prosody may result from extensive reading experience—and that dyslexic difficulties in metacognitive access to lexical stress arise due to limited exposure to reading—we speculate that the contribution of the frequently reported cognitive deficit in DD cannot be ruled out. This would further expand the Cognitive Mediation Hypothesis.

As an alternative or possibly complementary perspective, the finding that both our adolescent and child participants with DD processed weak syllables similarly to TD participants—unlike English-speaking adults in Rathcke and Lin (2021)'s study—suggests that cross-language differences, possibly varying degrees of transparency, alongside reading experience and cognitive resources, may influence access to lexical stress representations. More specifically, Rathcke and Lin (2021) found that English-speaking adults with DD aligned significantly less with vowels in weak syllables compared to those in strong syllables. Whether this reflects a compensatory strategy remains unclear, but notably, this pattern did not emerge among Italian adolescents in the sensorimotor task. Given the higher variability associated with lexical stress cues in English compared to Italian (Colombo, 1992; Mousikou et al., 2024), it is possible that this variability reduces the necessity for compensatory mechanism. Accordingly, this emphasizes the need to account for linguistic variations when investigating lexical stress deficits in DD.

#### **4.5 Phonological Deficits in DD: Exploring the Nature of Impaired Cognitive Mediation**

While group-level differences in phonological identification were mediated by cognitive resources in the phoneme monitoring tasks across both adolescents and children, the nature of this mediation varied across the studies. Adolescents with DD exhibited consistently slower phoneme identification, which did not vary in proportion to their shifting attention scores. In contrast, TD adolescents with high shifting attention demonstrated higher phonological identification rates, whereas those with low shifting attention performed poorly on the phoneme monitoring task. These results can be interpreted as indicative of a potential dissociation between phonological processing and cognitive resources in DD, in light of the brain connectivity deficits hypothesis (Habib, 2021; Lou et al., 2019; Paulesu et al., 1996). This account suggests that DD arises due to weaker, absent, or deviant connections in the left hemisphere, particularly in brain areas responsible for language and cognitive processing. Within this theoretical framework, adolescents with DD may have received less cognitive support from attentional resources and executive functions, as a consequence of impaired neural connections between networks responsible for the interaction between these domains. However, this disconnectivity pattern was not replicated in children, where, instead, a significant correlation was observed between the composite

cognitive factor—encompassing IQ score, shifting attention score, working memory score, and age—and pupil responses during the correct rejection of non-targets, thus suggesting an alternative explanation for the mediating role of cognitive resources in phonological processing. Specifically, according to the proposal by Marini et al. (2013) distractor processing involves a filtering mechanism, which incurs a behavioral cost in no-distractor trials. This attentional cost, as suggested by Sabri et al. (2014) places a load on working memory, thereby reducing the available resources for executive function and attentional processes directed at target identification. Given that children with DD exhibited a lower pupil diameter while processing distractors yet were able to process a greater number of distractors but only a limited number of targets, and considering their lower working memory and shifting attention scores compared to TD peers, their performance was interpreted as a consequence of limited cognitive resources at the level of the filtering process. This limitation is likely due to the overloading effect of working memory on shifting attention. Within this framework, DD performance is not driven by a deficit in a single cognitive domain but rather by the interaction of multiple cognitive processes involved in the filtering of distractors. This interaction, rather than an isolated impairment, provides a more comprehensive context for understanding the performance patterns observed in children with DD. This explanation is supported by pupillometry studies showing that when cognitive resources, particularly attentional capacity, are reduced—such as in older adults compared to younger individuals—pupil size increases in response to task demands but exhibits a generally smaller overall dilation (Piquado et al., 2010; Tekin et al., 2018; Zhao et al., 2019).

Several factors may explain and potentially reconcile the different types of cognitive mediation emerging from our results in adolescents compared to children. Notably, socioeconomic status (SES) has been strongly linked to reading abilities, phonological and cognitive processing (Boman, 2023; Fluss et al., 2009; Noble et al., 2006). Specifically, higher SES levels are associated with overall higher language abilities. Accordingly, Meixner et al. (2019) demonstrated that reading experience enhances shifting attention and executive functioning. Notably, the adolescents of studies 1 and 2 were primarily recruited from public schools, conversely, several private schools participated in the studies 3 and 4 involving children. This distinction is particularly noteworthy because, the TD groups, which are expected to be characterized by enhanced and more efficient reading exposure compared to DD groups, displayed a heterogeneous profile. Adolescents generally exhibited lower working memory scores ( $M$  adolescents = 28;  $M$  children = 70) and shifting attention scores ( $M$  adolescents = 70;  $M$  children = 58) compared to children. Additionally, three adolescent participants scored below the 10th percentile on the shifting attention measure, despite demonstrating average academic performance and language proficiency in both L1 and L2, with no official diagnosis of

cognitive or language deficits. This raises the possibility that lower SES levels in adolescents may have contributed to a higher prevalence of less proficient readers in TD, leading to reduced phonological and cognitive abilities. Conversely, higher SES levels in children may have mitigated this effect by providing greater reading exposure, thereby enhancing language and cognitive resources. Given that we did not control for reading experience, this remains a valuable point for future research. However, while it is true that reading experience can influence language and cognitive abilities, the reverse relationship cannot be ruled out (Commodari & Guarnera, 2005). Therefore, we argue that reading exposure and SES should be considered as concurrent contributors, rather than as the sole explanatory model for the observed data.

An additional contributing factor involves the role of IQ as a controlling variable for cognitive variability and compensatory effects (Reis et al., 2000; van Viersen et al., 2019). In the studies 3 and 4 with children, we constructed a composite cognitive index, incorporating IQ, to obtain a more balanced and comprehensive measure of individual cognitive profiles. This approach helped control for potential confounding effects and allowed for a more effective assessment of cognitive-linguistic interactions. Conversely, in adolescents, shifting attention and working memory were used as covariates in the absence of IQ as a controlling factor. Although IQ and higher-order cognitive functions are correlated, they are still considered independent constructs (Blair, 2006). Notably, it is not uncommon for studies to report group-level differences that disappear after controlling for IQ, emphasizing its crucial role in balancing cognitive variability across groups and better accounting for subtle compensatory abilities (Cowan et al., 2017; Ladányi et al., 2023). Accordingly, high IQ can lead to compensatory strategy in DD (Reis et al., 2000; van Viersen et al., 2019). Therefore, in the absence of IQ as a controlling factor, it is plausible that some of our adolescents with DD who exhibited high phonological performance may have possessed other cognitive abilities associated with overall higher cognitive functioning, possibly driven by high IQ. These cognitive strengths could have contributed to sustaining their linguistic outcomes, thus aligning with an overloaded filtering cost process underlying the nature of cognitive mediation in DD.

Lastly, it is possible that adults, unlike children, tend to rely more on specific resources, such as attention, to compensate for phonological and reading difficulties (Protopapa & Smith-Spark, 2022). This, in turn, may further highlight the disconnection between these areas, which might be less pronounced in childhood, leading to a less refined but more comprehensive cognitive recruitment.

Therefore, although the current data cannot provide conclusive evidence on the nature of the impairment underlying the mediating role of cognition in accessing phonemes in DD, and eventually further research is needed to clarify this relationship, both interpretations of the present data—the disconnection hypothesis (Paulesu et al., 1996) and the cost-filtering process based on the joint effect

of working memory on shifting attention (Marini et al., 2013; Sabri et al., 2014)—seem to converge on one point: that this cognitive mediation is primarily driven by an inefficient interaction between several cognitive abilities, possibly mediated by IQ. This interpretation would not only reconcile previous findings suggesting that deficits in specific domains, such as attention or working memory, can prevent access to phonemes (Lallier et al., 2010; Ramus & Szenkovits, 2008) , but also align with McNeill et al. (2025), who conducted a study on a larger cohort of pre-literacy children and demonstrated how several cognitive functions contribute to phonological awareness and interact differently across various developmental stages. This, in turn, aligns with the twice-exceptionality view of how remediation works in DD (Foley Nicpon et al., 2011; van Viersen et al., 2019) which assumes that both cognitive strengths and weaknesses play a role in shaping reading deficits in individuals with DD.

## 5. Conclusion

This thesis provides evidence that Italian DD is indeed associated with impaired phonological processing (Ramus & Szenkovits, 2008; Snowling, 2003; Tallal, 1980; Thomson & Goswami, 2010; Vellutino et al., 2004), which remains stable from late childhood to adolescence, despite the influence of higher language transparency (Hengeveld & Leufkens, 2018; Landerl et al., 2013). Furthermore, these phonological deficits appear comparable in both isolated DD and DD comorbid with dyscalculia. However, these impairments cannot be attributed to reduced acoustic sensitivity to prominence or lexical stress, as the acoustic features of lexical stress were processed similarly across TD and DD participants, regardless of age. Likewise, they are not driven by difficulties in decoding acoustic cues related to segmental contrasts.

However, although phonemes and lexical stress processing was comparable across clinical and non-clinical groups, some differences emerged as a function of age. One key finding reveals that the ability to efficiently use the gemination/singleton contrast to facilitate access to phoneme is still not fully adult-like in Italian children aged 8 to 10. Similarly, the ability to effectively use lexical stress for phonological processing was weaker in children compared to adolescents. Notably, in alignment with Caccia et al. (2019), and contrary to previous studies, the primary acoustic cue underlying lexical stress processing across our child participants was pitch.

Overall, the findings emerging from the four studies of this thesis challenge the acoustic sensitivity hypothesis underlying lexical stress (Caccia et al., 2019; Goswami, 2011; Leong et al., 2011; Tierney & Kraus, 2013), as they do not support the presence of fragile or impaired representations of lexical stress in DD. If such impairments were present, they should have led to deficits in segmental representations, which were likewise intact across our DD participants. Conversely, the current results suggest that the core phonological deficit in children and adolescents with Italian DD lies in accessing phonological representations. In alignment with the Cognitive Mediation Hypothesis (Lallier et al., 2010; Ramus & Szenkovits, 2008), the thesis confirms that this observed impairment in accessing phonological representations is mediated by cognitive resources. Although the precise nature of this mediation remains partially unresolved, there is evidence of an inefficient interaction between cognitive abilities, possibly modulated by IQ, in sustaining phonological processing in Italian DD.

It is noteworthy that the present results ought to be considered preliminary, given the relatively small sample size, differences in SES that hinder comparability, and the wide range of participant ages included in the four studies of the present thesis. Additionally, some methodological

constraints, such as the absence of a comprehensive assessment (e.g., standardized reading tests and previous reading experience) and the inconsistent control of multiple cognitive resources, may have influenced the findings. As a consequence, the applicability of the findings of the present thesis to clinical practice relies on rigorous replication with larger participant samples and a more extensive consideration of individual cognitive and linguistic variables (McBride-Chang et al., 1996; Vozzi et al., 2021). Furthermore, test-retest reliability checks of the main findings (cf. Drost, 2011; Shadish et al., 2002) would provide additional empirical support for the interpretations presented here. Nevertheless, the present thesis has important theoretical and clinical implications and provide valuable directions for future research.

One primary implication is that stress sensitivity successfully interacts with phoneme identification, increasing the salience of phonemes in stressed syllables, regardless of clinical condition and language typology. However, since the magnitude of this perceptual advantage varies slightly between adolescence and late childhood, further research is needed to trace the detailed developmental trajectories of this interaction in both clinical and non-clinical populations. As it stands, this perceptual advantage provided by stress could be considered in clinical phonological training for individuals with DD to enhance the salience of challenging phonemes. The lack of group-level differences in stress sensitivity between DD and TD individuals observed across our studies can be reconciled with previous research highlighting stress deficits in DD, in light of the notion of prosodic competence proposed by Wade-Woolley et al. (2021). Within this framework, prosodic sensitivity appears to be a distinct and independent skill compared to prosodic awareness, though both contribute to the acquisition of comprehensive prosodic competence. Therefore, impairment in one component does not necessarily result in impairment in the other. This means, that following the meta-analysis by Mundy and Wood (2024) the absence of a deficit in stress sensitivity in DD does not rule out the presence of impairments in stress awareness. These abilities may develop at different times, following independent paths compared to segmental features, and progressively integrating in late childhood (Arciuli & Ballard, 2017; Quam & Swingley, 2014; Schild et al., 2014). Future research should consider comparing cognitive and metacognitive tasks within a longitudinal design to fully assess prosodic competence in individuals with DD and its interplay with phonology.

A second implication is that the combined and simultaneous effects of multiple cognitive resources, whether deficient or not, adjusted for age and IQ, rather than the isolated effect of a single cognitive component, seem to hinder access to phonemes in DD. Although the impact of cognitive functions on phoneme awareness is not new in the literature, the current studies demonstrates that this impact arises from complex interactions. In this regard, we align with McNeill et al. (2025), who demonstrated the interconnected nature of phoneme awareness and cognitive skills in a great cohort

of pre-literacy children, further emphasizing the necessity of tracing the developmental trajectories of these interconnections.

With regard to Italian research, two key findings can be highlighted. First, in alignment with Caccia et al. (2019), pitch appears to be the primary correlate of stress perception in children. Second, the lack of a perceptual advantage of geminates over singleton consonants in Italian children suggests that this phonological contrast is still evolving and requires further investigation. This is particularly relevant because gemination is processed differently across Italian varieties (Bertinetto & Loporcaro, 2005; Mairano & De Iacovo, 2020) potentially leading to different developmental trajectories with cascading effects on spelling ability during the emergence of literacy. In addition, given that this perceptual immaturity is still present in late childhood, a potential hierarchy in DD phonological remediation goals could be traced based on the present data, where training could be introduced later in childhood, following the mastery of other phonological contrasts.

Furthermore, the current thesis acknowledges the role of language typology when investigating phonological deficits across different linguistic backgrounds. To this point, the present data confirm that Italian adolescents with DD, differently from their English counterparts, did not exhibit a reduction in the alignment of weak syllables as a compensatory strategy in the same task of sensorimotor synchronization. In addition, none of our children considered rise time a significant correlate underlying lexical stress, thus confirming the specificity of acoustic cues behind lexical stress (Guo, 2022; Mousikou et al., 2024; Plag et al., 2011). This further aligns with previous findings suggesting that DD manifestations, as is the case with other language disorders, are shaped by the linguistic environment (Landerl et al., 2013). Given that both reading exposure and socioeconomic status (SES) might indirectly mediate phonological competence (Boman, 2023; Fluss et al., 2009; Noble et al., 2006), we propose that these factors, along with the degree of language transparency, should be strongly considered and retained in a multifactorial model of DD.

Overall, this thesis confirms the consistent nature of phonological challenges in Italian individuals with DD in both late childhood and adolescence, regardless of the presence or absence of comorbid dyslexia. These challenges manifest as impaired phonological access, possibly stemming from an inefficient interaction between underlying cognitive factors, a phenomenon that requires further investigation through comprehensive cognitive assessments for a clearer understanding. In this regard, pupil responses seem to be a reliable index for capturing this interplay and should be considered in future research. Although acoustic sensitivity to stress did not mediate these phonological difficulties across our participants, the hypothesis of a deficit in accessing lexical stress representations cannot be ruled out based on the current data. This further supports the multicomponential nature of prosodic competence. Notably, pitch was confirmed as a primary

correlate underlying the perception of lexical stress in Italian children, along with duration, but not rise time, thus highlighting the difficulty in extending findings on lexical stress impairments in Italian from those based on English-speaking participants. Furthermore, the ability to process lexical stress contrasts and gemination contrasts to facilitate phoneme access was weaker in children compared to adolescents, suggesting a non-adult-like processing pattern persisting into late childhood. This, in turn, appears to expand the concept of prosodic competence and possibly that of phonological competence. Longitudinal and cross-linguistic studies—including SES, comprehensive cognitive assessments, and comparisons between metacognitive and non-metacognitive tasks—are needed to further generalize these findings across languages.

## 6. References

- Abboub, N., Boll-Avetisyan, N., Bhatara, A., Höhle, B., & Nazzi, T. (2016). An Exploration of Rhythmic Grouping of Speech Sequences by French- and German-Learning Infants. *Frontiers in Human Neuroscience*, 10, 292. <https://doi.org/10.3389/fnhum.2016.00292>
- Abrams, D. A., Nicol, T., Zecker, S., & Kraus, N. (2009). Abnormal cortical processing of the syllable rate of speech in poor readers. *Journal of Neuroscience*, 29(24), 7686-7693. <https://doi.org/10.1523/jneurosci.5242-08.2009>
- Al Dahhan, N. Z., Kirby, J. R., & Munoz, D. P. (2016). Understanding Reading and Reading Difficulties Through Naming Speed Tasks: Bridging the Gaps Among Neuroscience, Cognition, and Education. *AERA Open*, 2(4), 2332858416675346. <https://doi.org/10.1177/2332858416675346>
- Alosh, M., Huque, M. F., Bretz, F., & D'Agostino, R. B. (2017). Tutorial on statistical considerations on subgroup analysis in confirmatory clinical trials. *Statistics in Medicine*, 36(8), 1334-1360. <https://doi.org/10.1002/sim.7167>
- American Psychiatric Association (2022). *Diagnostic and statistical manual of mental disorders: DSM-5-TR (Fifth edition, text revision)*. American Psychiatric Association Publishing.
- Anastasiou, D., & Protopapas, A. (2014). Difficulties in Lexical Stress Versus Difficulties in Segmental Phonology Among Adolescents With Dyslexia. *Scientific Studies of Reading*. <https://doi.org/10.1080/10888438.2014.934452>
- Andresen, A., & Monsrud, M.-B. (2022). Assessment of Dyslexia – Why, When, and with What? *Scandinavian Journal of Educational Research*, 66(6), 1063-1075. <https://doi.org/10.1080/00313831.2021.1958373>
- Andrikopoulou, A., Protopapas, A., & Arvaniti, A. (2021). Lexical stress representation in spoken word recognition. *Journal of Experimental Psychology: Human Perception and Performance*, 47(6), 830-851. <https://doi.org/10.1037/xhp0000929>
- Angelelli, P., Marinelli, C. V., Iaia, M., Putzolu, A., Gasperini, F., Brizzolaro, D., & Chilosi, A. M. (2016). Spelling Impairments in Italian Dyslexic Children with and without a History of Early Language Delay. Are There Any Differences? *Frontiers in Psychology*, 7. <https://doi.org/10.3389/fpsyg.2016.00527>
- Arciuli, J., & Ballard, K. J. (2017). Still not adult-like: lexical stress contrastivity in word productions of eight- to eleven-year-olds. *Journal of Child Language*, 44(5), 1274-1288. <https://doi.org/10.1017/s0305000916000489>
- Ardila, A., Bertolucci, P. H., Braga, L. W., Castro-Caldas, A., Judd, T., Kosmidis, M. H., Matute, E., Nitrini, R., Ostrosky-Solis, F., & Rosselli, M. (2010). Illiteracy: The Neuropsychology of Cognition Without Reading. *Archives of Clinical Neuropsychology*, 25(8), 689-712. <https://doi.org/10.1093/arclin/acq079>
- AudacityTeam. (2014). *Audacity®: Free audio editor and recorder (Version 2.0.0)* [Computer software]. <http://audacity.sourceforge.net/>

- Avesani, C., & Vayra, M. (2005). Accenting, deaccenting and information structure in Italian dialogue. In *Proceedings of the 6th SIGdial Workshop on Discourse and Dialogue*.
- Baayen, R. H. (2008). *Analyzing Linguistic Data: A Practical Introduction to Statistics using R*. Cambridge University Press. [https://doi.org/DOI: 10.1017/CBO9780511801686](https://doi.org/DOI:10.1017/CBO9780511801686)
- Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, 4(10), 829-839. <https://doi.org/10.1038/nrn1201>
- Barbiero, C., Montico, M., Lonciari, I., Monasta, L., Penge, R., Vio, C., Tressoldi, P. E., Carrozzini, M., De Petris, A., De Cagno, A. G., Crescenzi, F., Tinarelli, G., Leccese, A., Pinton, A., Belacchi, C., Tucci, R., Musinu, M., Tossali, M. L., Antonucci, A. M., Perrone, A., Lentini, Graziano, M., & Ronfani, L. (2019). The lost children: The underdiagnosis of dyslexia in Italy. A cross-sectional national study. *PLoS One*, 14(1), e0210448. <https://doi.org/10.1371/journal.pone.0210448>
- Barbosa, T., Rodrigues, C. C., Mello, C. B., Silva, M., & Bueno, O. F. A. (2019). Executive functions in children with dyslexia. *Arquivos de Neuro-Psiquiatria*, 77(4), 254-259. <https://doi.org/10.1590/0004-282x20190033>
- Baroni, A. (2014). On the importance of being noticed: the role of acoustic salience in phonotactics (and casual speech). *Language Sciences*, 46, 18-36. <https://doi.org/https://doi.org/10.1016/j.langsci.2014.06.004>
- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, 68(3). <https://doi.org/10.1016/j.jml.2012.11.001>
- Barry, J. G., Harbodt, S., Cantiani, C., Sabisch, B., & Zobay, O. (2012). Sensitivity to lexical stress in dyslexia: a case of cognitive not perceptual stress. *Dyslexia*, 18(3), 139-165. <https://doi.org/10.1002/dys.1440>
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1), 1 - 48. <https://doi.org/10.18637/jss.v067.i01>
- Baumann, S., & Winter, B. (2018). *What makes a word prominent? Predicting untrained German listeners' perceptual judgments* (Vol. 70). <https://doi.org/10.1016/j.wocn.2018.05.004>
- Becková, A., Rudolfová, V., Horáček, J., & Nekovářová, T. (2022). Unraveling the Filled Duration Illusion and its Stability in Repeated Measurements: Acoustic Stimuli and the Possible Prospect for Time in Music. *Music Perception*, 40(2), 135-149. <https://doi.org/10.1525/mp.2022.40.2.135>
- Bedoin, N., Brisseau, L., Molinier, P., Roch, D., & Tillmann, B. (2016). Temporally Regular Musical Primes Facilitate Subsequent Syntax Processing in Children with Specific Language Impairment. *Frontiers in Neuroscience*, 10(245). <https://doi.org/10.3389/fnins.2016.00245>

- Bégel, Bella, D., Devignes, Vandenbergue, Lemaître, & Dellacherie. (2022, Feb). Rhythm as an independent determinant of developmental dyslexia. *Developmental Psychology*, 58(2), 339-358. <https://doi.org/10.1037/dev0001293>
- Belacchi, C., Scalisi, T. G., Cannoni, E., & Cornoldi, C. (2008). *Manuale CPM. Coloured Progressive Matrices. Standardizzazione Italiana*. Firenze: Giunti OS Organizzazioni Speciali.
- Benndorf, V., Rau, H., & Sslch, C. (2014). Minimizing Learning Behavior in Experiments with Repeated Real-Effort Tasks. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.2503029>
- Berent, I., Vaknin-Nusbaum, V., Balaban, E., & Galaburda, A. M. (2012). Dyslexia Impairs Speech Recognition but Can Spare Phonological Competence. *PLoS One*, 7(9), e44875. <https://doi.org/10.1371/journal.pone.0044875>
- Bernard, C., & Gervain, J. (2012). Prosodic cues to word order: what level of representation? *Frontiers in Psychology*, 3, 451. <https://doi.org/10.3389/fpsyg.2012.00451>
- Bertinetto, & Loporcaro. (2005). The sound pattern of Standard Italian, as compared with the varieties spoken in Florence, Milan and Rome. *Journal of the International Phonetic Association*, 35, 131-151. <https://doi.org/10.1017/S0025100305002148>
- Bertinetto, P. M. (1980). The perception of stress by Italian speakers. *Journal of Phonetics*, 8(4), 385-395. [https://doi.org/https://doi.org/10.1016/S0095-4470\(19\)31495-0](https://doi.org/https://doi.org/10.1016/S0095-4470(19)31495-0)
- Bitirgen, G., Daraghma, M., & Özkağnıcı, A. (2019). Evaluation of Pupillary Light Reflex in Amblyopic Eyes Using Dynamic Pupillometry. *Turkish Journal of Ophthalmology*, 49(6), 310-314. <https://doi.org/10.4274/tjo.galenos.2019.32748>
- Black, J. W., Hay, J., Clark, L., & Brand, J. (2023). The overlooked effect of amplitude on within-speaker vowel variation. *Linguistics Vanguard*, 9(1), 173-189. <https://doi.org/doi:10.1515/lingvan-2022-0086>
- Blair, C. (2006). How similar are fluid cognition and general intelligence? A developmental neuroscience perspective on fluid cognition as an aspect of human cognitive ability. *Behavioral and Brain Sciences*, 29(2), 109-125. <https://doi.org/10.1017/S0140525X06009034>
- Blomert, L., & Mitterer, H. (2004). The fragile nature of the speech-perception deficit in dyslexia: natural vs synthetic speech. *Brain and Language*, 89(1), 21-26. [https://doi.org/10.1016/s0093-934x\(03\)00305-5](https://doi.org/10.1016/s0093-934x(03)00305-5)
- Boersma, P., & Weenink, D. (2007). *PRAAT: Doing phonetics by computer* (Version 5.3.51) [Computer software]. <http://www.praat.org/>.
- Bogliotti, C., Serniclaes, W., Messaoud-Galusi, S., & Sprenger-Charolles, L. (2008). Discrimination of speech sounds by children with dyslexia: comparisons with chronological age and reading level controls. *Journal of experimental child psychology*, 101(2), 137-155. <https://doi.org/10.1016/j.jecp.2008.03.006>

- Boman, B. (2023). The influence of SES, cognitive, and non-cognitive abilities on grades: cross-sectional and longitudinal evidence from two Swedish cohorts. *European Journal of Psychology of Education*, 38(2), 587-603. <https://doi.org/10.1007/s10212-022-00626-9>
- Bonacina, S., Krizman, J., White-Schwoch, T., Nicol, T., & Kraus, N. (2019). How Rhythmic Skills Relate and Develop in School-Age Children. *Global pediatric health*, 6, 2333794X19852045-12333794X19852045. <https://doi.org/10.1177/2333794X19852045>
- Borghans, L., Golsteyn, B. H., Heckman, J. J., & Humphries, J. E. (2016). What grades and achievement tests measure. *Proceedings of the National Academy of Sciences of the United States of America, U S A*, 113(47), 13354-13359. <https://doi.org/10.1073/pnas.1601135113>
- Bortolini, U., & Leonard, L. B. (1996). Phonology and grammatical morphology in specific language impairment: Accounting for individual variation in English and Italian. *Applied Psycholinguistics*, 17(1), 85-104. <https://doi.org/10.1017/S0142716400009474>
- Boswijk, V., Loerts, H., & Hilton, N. H. (2020). Salience is in the eye of the beholder: Increased pupil size reflects acoustically salient variables. *Ampersand*, 7, 100061. <https://doi.org/https://doi.org/10.1016/j.amper.2020.100061>
- Braz, C. H., Gonçalves, L. F., Paiva, K. M., Haas, P., & Patatt, F. S. A. (2021). Implications of musical practice in central auditory processing: a systematic review. *Brazilian Journal of Otorhinolaryngology*, 87(2), 217-226. <https://doi.org/https://doi.org/10.1016/j.bjorl.2020.10.007>
- Breier, J. I., Gray, L., Fletcher, J. M., Diehl, R. L., Klaas, P., Foorman, B. R., & Molis, M. R. (2001). Perception of Voice and Tone Onset Time Continua in Children with Dyslexia with and without Attention Deficit/Hyperactivity Disorder. *Journal of experimental child psychology*, 80(3), 245-270. <https://doi.org/https://doi.org/10.1006/jecp.2001.2630>
- Broś, K., Meyer, M., Kliesch, M., & Dellwo, V. (2021). Word stress processing integrates phonological abstraction with lexical access – An ERP study. *Journal of neurolinguistics*, 57, 100959. <https://doi.org/https://doi.org/10.1016/j.jneuroling.2020.100959>
- Bryant, P. E., & Bradley, L. (1983). Auditory organization and backwardness in reading. In M. Rutter (Ed.), *Developmental neuropsychiatry*. Guilford.
- Cabrera, L., & Gervain, J. (2020). Speech perception at birth: The brain encodes fast and slow temporal information. *Sci Adv*, 6(30), eaba7830. <https://doi.org/10.1126/sciadv.aba7830>
- Caccia, M., & Lorusso, M. (2020). The processing of rhythmic structures in music and prosody by children with developmental dyslexia and developmental language disorder. *Developmental Science*. <https://doi.org/10.1111/desc.12981>
- Caccia, M., Presti, G., Toraldo, A., Radaelli, A., Ludovico, L. A., Ogliari, A., & Lorusso, M. L. (2019). Pitch as the Main Determiner of Italian Lexical Stress Perception Across the Lifespan: Evidence From Typical Development and Dyslexia. *Frontiers in Psychology*, 10(1458). <https://doi.org/10.3389/fpsyg.2019.01458>

- Cardoso, A. M., Silva, M. M., & Pereira, M. M. (2013). Phonological awareness and the working memory of children with and without literacy difficulties. *Codas*, 25(2), 110-114. <https://doi.org/10.1590/s2317-17822013000200004>
- Carioti, D., Masia, M. F., Travellini, S., & Berlingeri, M. (2021). Orthographic depth and developmental dyslexia: a meta-analytic study. *Annals of Dyslexia*, 71(3), 399-438. <https://doi.org/10.1007/s11881-021-00226-0>
- Carroll, J. M., Snowling, M. J., Hulme, C., & Stevenson, J. (2003). The development of phonological awareness in preschool children. *Developmental Psychology*, 39(5), 913-923. <https://doi.org/10.1037/0012-1649.39.5.913>
- Casini, L., Pech-Georgel, C., & Ziegler, J. C. (2018). It's about time: revisiting temporal processing deficits in dyslexia. *Developmental Science*, 21(2). <https://doi.org/10.1111/desc.12530>
- Castellotti, S., D'Agostino, O., Biondi, A., Pignatiello, L., & Del Viva, M. M. (2022). Influence of Motor and Cognitive Tasks on Time Estimation. *Brain Sci*, 12(3). <https://doi.org/10.3390/brainsci12030404>
- Castles, A., & Coltheart, M. (2004). Is there a causal link from phonological awareness to success in learning to read? *Cognition*, 91(1), 77-111. [https://doi.org/10.1016/s0010-0277\(03\)00164-1](https://doi.org/10.1016/s0010-0277(03)00164-1)
- Chen, O., Paas, F., & Sweller, J. (2023). A Cognitive Load Theory Approach to Defining and Measuring Task Complexity Through Element Interactivity. *Educational psychology review*, 35(2), 63. <https://doi.org/10.1007/s10648-023-09782-w>
- Cheng, C., Yao, Y., Wang, Z., & Zhao, J. (2021). Visual attention span and phonological skills in Chinese developmental dyslexia. *Research in developmental disabilities*, 116, 104015. <https://doi.org/10.1016/j.ridd.2021.104015>
- Chiappe, P., Chiappe, D. L., & Siegel, L. S. (2001). Speech Perception, Lexicality, and Reading Skill. *Journal of experimental child psychology*, 80(1), 58-74. <https://doi.org/https://doi.org/10.1006/jecp.2000.2624>
- Chiossi, J. S. C., Patou, F., Ng, E. H. N., Faulkner, K. F., & Lyxell, B. (2023). Phonological discrimination and contrast detection in pupillometry. *Frontiers in Psychology*, 14. <https://doi.org/10.3389/fpsyg.2023.1232262>
- Chu, M., & Feng, Y. (2001). *Study on factors influencing durations of syllables in Mandarin*. <https://doi.org/10.21437/Eurospeech.2001-180>
- Chutko, L. S., Surushkina, S. Y., Yakovenko, E. A., Anisimova, T. I., Didur, M. D., & Chekalova, S. A. (2022). Impairments to Executive Functions in Children with Dyslexia. *Neuroscience and Behavioral Physiology*, 52(1), 1-7. <https://doi.org/10.1007/s11055-022-01200-y>
- Clark, W. A. V., & Avery, K. L. (1976). The Effects of Data Aggregation in Statistical Analysis. *Geographical Analysis*, 8(4), 428-438. <https://doi.org/https://doi.org/10.1111/j.1538-4632.1976.tb00549.x>

- Cohen, M. (2001). An integrative theory of prefrontal cortex function. *Annual review of neuroscience*, 24, 167-202.
- Colling, Noble, & Goswami. (2017). Neural Entrainment and Sensorimotor Synchronization to the Beat in Children with Developmental Dyslexia: An EEG Study. *Frontiers in Neuroscience*, 11, 360. <https://doi.org/10.3389/fnins.2017.00360>
- Colombo, L. (1992). Lexical Stress Effect and Its Interaction With Frequency in Word Pronunciation. *Journal of experimental psychology. Human perception and performance*, 18(4), 987-1003. <https://doi.org/10.1037/0096-1523.18.4.987>
- Commodari, E., & Guarnera, M. (2005). Attention and reading skills. *Perceptual and Motor Skills*, 100(2), 375-386. <https://doi.org/10.2466/pms.100.2.375-386>
- Conway, A. R., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005, Oct). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review*, 12(5), 769-786. <https://doi.org/10.3758/bf03196772>
- Cornoldi, C., Re, A. M., & Tressoldi, P. E. (2012). *Batteria per la Valutazione della Scrittura e della Competenza Ortografica - 2 (BVSCO-2)*. GIUNTI O.S.
- Cornoldi, C., & Tressoldi, P. (2014). Linee guida per la diagnosi dei profili di dislessia e disortografia previsti dalla legge 170: Invito a un dibattito. *Psicologia Clinica Dello Sviluppo*, 18, 75-92. <https://doi.org/10.1449/77111>
- Corriveau, & Goswami. (2009, Jan). Rhythmic motor entrainment in children with speech and language impairments: tapping to the beat. *Cortex*, 45(1), 119-130. <https://doi.org/10.1016/j.cortex.2007.09.008>
- Corriveau, Pasquini, & Goswami. (2007, Jun). Basic auditory processing skills and specific language impairment: a new look at an old hypothesis. *Journal of Speech, Language, and Hearing Research*, 50(3), 647-666. [https://doi.org/10.1044/1092-4388\(2007/046\)](https://doi.org/10.1044/1092-4388(2007/046))
- Cotter, J., Schmiede, S., Moss, A., & Ambroggio, L. (2023). How to Interact With Interactions: What Clinicians Should Know About Statistical Interactions. *Hospital Pediatrics*, 13(10), e319-e323. <https://doi.org/10.1542/hpeds.2023-007259>
- Cotton, S., & Crewther, S. (2009). The Relationship Between Reading and Intelligence in Primary School Aged Children: Implications for Definitional Models of Dyslexia. *The Open Education Journal*, 2. <https://doi.org/10.2174/1874920800902010042>
- Cowan, N., Hogan, T. P., Alt, M., Green, S., Cabbage, K. L., Brinkley, S., & Gray, S. (2017). Short-term Memory in Childhood Dyslexia: Deficient Serial Order in Multiple Modalities. *Dyslexia*, 23(3), 209-233. <https://doi.org/10.1002/dys.1557>
- Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika*, 16, 297-334. <https://doi.org/10.1007/BF02310555>
- Crow, E. L. (1988). *Lognormal distributions: Theory and applications* (1st ed.). Routledge. <https://doi.org/10.1201/9780203748664>

- Crowe, S. F. (2000). Does the letter number sequencing task measure anything more than digit span? *Assessment*, 7(2), 113–117. <https://doi.org/10.1177/107319110000700202>
- Cui, Z., Xia, Z., Su, M., Shu, H., & Gong, G. (2016). Disrupted white matter connectivity underlying developmental dyslexia: A machine learning approach. *Human Brain Mapping*, 37(4), 1443-1458. <https://doi.org/10.1002/hbm.23112>
- Cumming, R., Wilson, A., & Goswami, U. (2015). Basic auditory processing and sensitivity to prosodic structure in children with specific language impairments: a new look at a perceptual hypothesis [Original Research]. *Frontiers in Psychology*, 6(972). <https://doi.org/10.3389/fpsyg.2015.00972>
- Cumming, R., Wilson, A., Leong, V., Colling, L. J., & Goswami, U. (2015). Awareness of Rhythm Patterns in Speech and Music in Children with Specific Language Impairments. *Frontiers in Human Neuroscience*, 9(672). <https://doi.org/10.3389/fnhum.2015.00672>
- Cutler, & Butterfield. (1992). Rhythmic cues to speech segmentation: Evidence from juncture misperception. *Journal of Memory and Language*, 31(2), 218-236. [https://doi.org/https://doi.org/10.1016/0749-596X\(92\)90012-M](https://doi.org/https://doi.org/10.1016/0749-596X(92)90012-M)
- D'Imperio, M. (2002). Italian intonation: An overview and some questions. *International Journal of Latin & Romance Linguistics*, 14(1), 37. <https://doi.org/10.1515/prbs.2002.005>
- D'Imperio, M., & Rosenthal, S. (1999). Phonetics and phonology of main stress in Italian. *Phonology*, 16, 1-28. <https://doi.org/10.1017/S0952675799003681>
- Danelli, L., Berlinger, M., Bottini, G., Borghese, N. A., Lucchese, M., Sberna, M., Price, C. J., & Paulesu, E. (2017). How many deficits in the same dyslexic brains? A behavioural and fMRI assessment of comorbidity in adult dyslexics. *Cortex*, 97, 125-142. <https://doi.org/10.1016/j.cortex.2017.08.038>
- 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 Simone, E., Moll, K., & Beyersmann, E. (2024). Cross-Linguistic Differences in Morphological Processing: Evidence from English and Italian. *Scientific Studies of Reading*, 1-20. <https://doi.org/10.1080/10888438.2024.2413108>
- Dębska, A., Łuniewska, M., Zubek, J., Chyl, K., Dynak, A., Dziegiel-Fivet, G., Plewko, J., Jednoróg, K., & Grabowska, A. (2022). The cognitive basis of dyslexia in school-aged children: A multiple case study in a transparent orthography. *Dev Sci*, 25(2), e13173. <https://doi.org/10.1111/desc.13173>
- Degé, F., & Schwarzer, G. (2011). The Effect of a Music Program on Phonological Awareness in Preschoolers. *Frontiers in Psychology*, 2. <https://doi.org/10.3389/fpsyg.2011.00124>
- Demuth, K. (2015). Prosodic Licensing and the development of phonological and morphological representations. In A. Farris-Trimble & J. Barlow (Ed.), *Perspectives on Phonological Theory and Development: In honor of Daniel A. Dinnsen* (pp. 11-24). John Benjamins Publishing Company. <https://doi.org/10.1075/lald.56.04dem>

- Derawi, H., Reinisch, E., & Gabay, Y. (2022). Increased reliance on top-down information to compensate for reduced bottom-up use of acoustic cues in dyslexia. *Psychonomic Bulletin & Review*, 29(1), 281-292. <https://doi.org/10.3758/s13423-021-01996-9>
- Di Benedetto, M.-G. (2000). Gemination in Italian: the GEMMA project. *Journal of The Acoustical Society of America* 108. <https://doi.org/10.1121/1.4743263>
- Di Benedetto, M.-G., & De Nardis, L. (2021). Consonant gemination in Italian: The affricate and fricative case. *Speech Communication*, 134. <https://doi.org/10.1016/j.specom.2021.07.005>
- Dinno, A. (2015). Nonparametric pairwise multiple comparisons in independent groups using Dunn's test. *The Stata Journal*, 15(1), 292-300. <https://doi.org/10.1177/1536867X1501500117>
- Dmitrienko, A., Muysers, C., Fritsch, A., & Lipkovich, I. (2016). General guidance on exploratory and confirmatory subgroup analysis in late-stage clinical trials. *Journal of Biopharmaceutical Statistics*, 26(1), 71-98. <https://doi.org/10.1080/10543406.2015.1092033>
- Dmitrieva, O. (2014). *Sonority of adjacent segments in the perception of durational distinctions* (Vol. 135). <https://doi.org/10.1121/1.4877279>
- 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>
- Ebert, K. D., & Kohnert, K. (2011). Sustained attention in children with primary language impairment: a meta-analysis. *Journal of Speech, Language, and Hearing Research*, 54(5), 1372-1384. [https://doi.org/10.1044/1092-4388\(2011/10-0231\)](https://doi.org/10.1044/1092-4388(2011/10-0231))
- Egan, C., Payne, J. S., & Jones, M. W. (2023). The impact of phonological relatedness on semantic congruency judgements in readers with dyslexia: Evidence from behavioural judgements, event related potentials and pupillometry. *Neuropsychologia*, 184, 108548. <https://doi.org/10.1016/j.neuropsychologia.2023.108548>
- Ehri, L. (2005). Phases of Development in Learning to Read Words by Sight. *Journal of Research in Reading*, 18, 116-125. <https://doi.org/10.1111/j.1467-9817.1995.tb00077.x>
- Einfeldt, M., van de Weijer, J., & Kupisch, T. (2019, 11/04). The production of geminates in Italian-dominant bilinguals and heritage speakers of Italian. *Language, Interaction and Acquisition / Langage, Interaction et Acquisition*, 10, 177-203. <https://doi.org/10.1075/lia.18015.ein>
- Eloranta, A. K., Närhi, V. M., Eklund, K. M., Ahonen, T. P. S., & Aro, T. I. (2019). Resolving reading disability-Childhood predictors and adult-age outcomes. *Dyslexia*, 25(1), 20-37. <https://doi.org/10.1002/dys.1605>
- Eriksson, A., Suni, A., Vainio, M., & Šimko, J. (2018). The acoustic basis of lexical stress perception. In *Proceedings of Speech Prosody 2018*, Poznań, Poland.

- Esteve-Gibert, N., & Prieto, P. (2013). Prosody signals the emergence of intentional communication in the first year of life: evidence from Catalan-babbling infants. *Journal of Child Language*, *40*(5), 919-944. <https://doi.org/10.1017/S0305000912000359>
- Farquharson, K., Centanni, T. M., Franzluebbers, C. E., & Hogan, T. P. (2014). Phonological and lexical influences on phonological awareness in children with specific language impairment and dyslexia. *Frontiers in Psychology*, *5*, 838. <https://doi.org/10.3389/fpsyg.2014.00838>
- Farrar, M. J., & Ashwell, S. (2012). Phonological awareness, executive functioning, and theory of mind. *Cognitive Development*, *27*(1), 77-89. <https://doi.org/https://doi.org/10.1016/j.cogdev.2011.08.002>
- Fay, M. P., & Proschan, M. A. (2010). Wilcoxon-Mann-Whitney or t-test? On assumptions for hypothesis tests and multiple interpretations of decision rules. *Statistical Surveys*, *4*, 1-39. <https://doi.org/10.1214/09-ss051>
- Fernald, A. (1989). Intonation and communicative intent in mothers' speech to infants: Is the melody the message? *Child Development*, *60*(6), 1497–1510. <https://www.ncbi.nlm.nih.gov/pubmed/2612255>
- Ferrero, F. (1972). “Caratteristiche acustiche dei fonemi vocalici italiani” [Acoustic characteristics of vowel phonemes in Italian]. *Parole Metodi* *3*, 9-32.
- Fink, L., Simola, J., Tavano, A., Lange, E., Wallot, S., & Laeng, B. (2024). From pre-processing to advanced dynamic modeling of pupil data. *Behavior Research Methods*, *56*(3), 1376-1412. <https://doi.org/10.3758/s13428-023-02098-1>
- Fisher, C., & Tokura, H. (1996). Acoustic cues to grammatical structure in infant-directed speech: cross-linguistic evidence. *Child development*, *67*(6), 3192-3218.
- Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., & Schön, D. (2015). Music Training Increases Phonological Awareness and Reading Skills in Developmental Dyslexia: A Randomized Control Trial. *PLoS One*, *10*(9), e0138715. <https://doi.org/10.1371/journal.pone.0138715>
- Fluss, J., Ziegler, J. C., Warszawski, J., Ducot, B., Richard, G., & Billard, C. (2009). Poor reading in French elementary school: The interplay of cognitive, behavioral, and socioeconomic factors. *Journal of Developmental & Behavioral Pediatrics*, *30*(3), 206–216. <https://doi.org/10.1097/DBP.0b013e3181a7ed6c>
- Foley Nicpon, M., Allmon, A., Sieck, B., & Stinson, R. D. (2011). Empirical Investigation of Twice-Exceptionality: Where Have We Been and Where Are We Going? *Gifted Child Quarterly*, *55*(1), 3-17. <https://doi.org/10.1177/0016986210382575>
- Foss, D., & Gernsbacher, M. A. (1983). Cracking the dual code: Toward a unitary model of phoneme identification. *Journal of Verbal Learning and Verbal Behavior*, *22*, 609–632. [https://doi.org/10.1016/S0022-5371\(83\)90365-4](https://doi.org/10.1016/S0022-5371(83)90365-4)
- Foss, D. J. (1969). Decision processes during sentence comprehension: Effects of lexical item difficulty and position upon decision times. *Journal of Verbal Learning and Verbal Behavior*, *8*, 457–462. [https://doi.org/10.1016/S0022-5371\(69\)80091-6](https://doi.org/10.1016/S0022-5371(69)80091-6)

- Foss, D. J., & Swinney, D. A. (1973). On the psychological reality of the phoneme: Perception, identification, and consciousness. *Journal of Verbal Learning and Verbal Behavior*, 12(3), 246-257. [https://doi.org/https://doi.org/10.1016/S0022-5371\(73\)80069-6](https://doi.org/https://doi.org/10.1016/S0022-5371(73)80069-6)
- Foss, S. (1973). On the psychological reality of the phoneme: Perception, identification, and consciousness. *Journal of Verbal Learning and Verbal Behavior*, 12, 246–257. [https://doi.org/10.1016/S0022-5371\(73\)80017-2](https://doi.org/10.1016/S0022-5371(73)80017-2)
- Fowler, A. E. (1991). How early phonological development might set the stage for phoneme awareness. In S. A. Brady & D. P. Shankweiler (Eds.), *Phonological processes in literacy: A tribute to Isabelle Y. Liberman* (pp. 97-117). Lawrence Erlbaum Associates, Inc.
- Fraser, J., Goswami, U., & Conti-Ramsden, G. (2010). Dyslexia and Specific Language Impairment: The Role of Phonology and Auditory Processing. *Scientific Studies of Reading*, 14(1), 8-29. <https://doi.org/10.1080/10888430903242068>
- Frazier, L., Carlson, K., & Clifton, C. (2006). Prosodic phrasing is central to language comprehension. *Trends in cognitive sciences*, 10, 244-249. <https://doi.org/10.1016/j.tics.2006.04.002>
- Galle, M. E., & McMurray, B. (2014). The development of voicing categories: A quantitative review of over 40 years of infant speech perception research. *Psychonomic Bulletin & Review*, 21(4), 884–906. <https://doi.org/10.3758/s13423-013-0569-y>
- García, A. M., de Leon, J., Tee, B. L., Blasi, D. E., & Gorno-Tempini, M. L. (2023). Speech and language markers of neurodegeneration: a call for global equity. *Brain*. <https://doi.org/10.1093/brain/awad253>
- Gathercole, S. E., Alloway, T. P., Willis, C., & Adams, A. M. (2006). Working memory in children with reading disabilities. *Journal of Experimental Child Psychology*, 93(3), 265–281. <https://doi.org/10.1016/j.jecp.2005.08.003>
- Gathercole, S. E., & Baddeley, A. D. (1995). Short-term memory may yet be deficient in children with language impairments: a comment on van der Lely & Howard (1993). *J Speech Hear Res*, 38(2), 463-472. <https://doi.org/10.1044/jshr.3802.463>
- Geng, J. (2014). Attentional Mechanisms of Distractor Suppression. *Current directions in psychological science*, 23, 147-153. <https://doi.org/10.1177/0963721414525780>
- Gervain, & Werker. (2013). Prosody cues word order in 7-month-old bilingual infants. *Nat Commun*, 4, 1490. <https://doi.org/10.1038/ncomms2430>
- Gervain, J., Nespor, M., Mazuka, R., Horie, R., & Mehler, J. (2008). Bootstrapping word order in prelexical infants: A Japanese-Italian cross-linguistic study. *Cognitive psychology*, 57, 56-74. <https://doi.org/10.1016/j.cogpsych.2007.12.001>
- Giofrè, D., Toffalini, E., Provazza, S., Calcagni, A., Altoè, G., & Roberts, D. J. (2019). Are children with developmental dyslexia all the same? A cluster analysis with more than 300 cases. *Dyslexia*, 25(3), 284-295. <https://doi.org/https://doi.org/10.1002/dys.1629>

- Giraud, A.-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: Emerging computational principles and operations. *Nature Neuroscience*, *15*(4), 511–517. <https://doi.org/10.1038/nn.3063>
- Goswami. (2011, 01/31). Temporal sampling framework for developmental dyslexia. *Trends in cognitive sciences*, *15*, 3-10. <https://doi.org/10.1016/j.tics.2010.10.001>
- Goswami, Cumming, Chait, Huss, Mead, Wilson, Barnes, & Fosker. (2016). Perception of Filtered Speech by Children with Developmental Dyslexia and Children with Specific Language Impairments. *Frontiers in Psychology*, *7*, 791-791. <https://doi.org/10.3389/fpsyg.2016.00791>
- Goswami, U., Fosker, T., Huss, M., Mead, N., & Szűcs, D. (2011). Rise time and formant transition duration in the discrimination of speech sounds: The Ba–Wa distinction in developmental dyslexia. *Developmental Science*, *14*(1), 34–43. <https://doi.org/10.1111/j.1467-7687.2010.00955.x>
- Goswami, Thomson, Richardson, Stainthorp, Hughes, Rosen, & Scott. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences of the United States of America*, *99*, 10911-10916. <https://doi.org/10.1073/pnas.122368599>
- Goswami, U. (2011). Temporal sampling framework for developmental dyslexia. *Trends in cognitive sciences*, *15*, 3-10. <https://doi.org/10.1016/j.tics.2010.10.001>
- Goswami, U. (2012). Phonological Representation. In N. M. Seel (Ed.), *Encyclopedia of the Sciences of Learning* (pp. 2625-2627). Springer US. [https://doi.org/10.1007/978-1-4419-1428-6\\_148](https://doi.org/10.1007/978-1-4419-1428-6_148)
- Goswami, U. (2019). Speech rhythm and language acquisition: an amplitude modulation phase hierarchy perspective. *Annals of the New York Academy of Sciences*, *1453*(1), 67-78. <https://doi.org/https://doi.org/10.1111/nyas.14137>
- Goswami, U., Fosker, T., Huss, M., Mead, N., & Szűcs, D. (2011). Rise time and formant transition duration in the discrimination of speech sounds: the Ba–Wa distinction in developmental dyslexia. *Developmental Science*, *14*(1), 34-43. <https://doi.org/https://doi.org/10.1111/j.1467-7687.2010.00955.x>
- Goswami, U., Huss, M., Mead, N., Fosker, T., & Verney, J. P. (2013, May). Perception of patterns of musical beat distribution in phonological developmental dyslexia: significant longitudinal relations with word reading and reading comprehension. *Cortex*, *49*(5), 1363-1376. <https://doi.org/10.1016/j.cortex.2012.05.005>
- Goswami, U., & Leong, V. (2013, 03/01). Speech rhythm and temporal structure: Converging perspectives? *Laboratory Phonology*, *4*, 67-92. <https://doi.org/10.1515/lp-2013-0004>
- Goswami, U., Mead, N., Fosker, T., Huss, M., Barnes, L., & Leong, V. (2013). Impaired perception of syllable stress in children with dyslexia: A longitudinal study. *Journal of Memory and Language*, *69*(1), 1-17. <https://doi.org/https://doi.org/10.1016/j.jml.2013.03.001>

- Gout, Christophe, & Morgan. (2004). Phonological phrase boundaries constrain lexical access II. Infant data. *Journal of Memory and Language*, 51, 548-567. <https://doi.org/10.1016/j.jml.2004.07.002>
- Green, P., & MacLeod, C. (2016). simr: an R package for power analysis of generalised linear mixed models by simulation. *Methods in Ecology and Evolution*, 7(4), 493-498. <https://doi.org/10.1111/2041-210X.12504>
- Gresch, D., Boettcher, S. E. P., van Ede, F., & Nobre, A. C. (2024). Shifting attention between perception and working memory. *Cognition*, 245, 105731. <https://doi.org/10.1016/j.cognition.2024.105731>
- Grosjean, F., & Gee, J. P. (1987, Mar). Prosodic structure and spoken word recognition. *Cognition*, 25(1-2), 135-155. [https://doi.org/10.1016/0010-0277\(87\)90007-2](https://doi.org/10.1016/0010-0277(87)90007-2)
- Grube, M., Cooper, F. E., Chinnery, P. F., & Griffiths, T. D. (2010). Dissociation of duration-based and beat-based auditory timing in cerebellar degeneration. *Proceedings of the National Academy of Sciences*, 107(25), 11597-11601. <https://doi.org/doi:10.1073/pnas.0910473107>
- Gunasekaran, H., Azizi, L., van Wassenhove, V., & Herbst, S. K. (2023). Characterizing endogenous delta oscillations in human MEG. *Scientific Reports*, 13(1), 11031. <https://doi.org/10.1038/s41598-023-37514-1>
- Guo, X. (2022). Acoustic Correlates of English Lexical Stress Produced by Chinese Dialect Speakers Compared to Native English Speakers. *Frontiers in Psychology*, 13. <https://doi.org/10.3389/fpsyg.2022.796252>
- Habib, M. (2021). The Neurological Basis of Developmental Dyslexia and Related Disorders: A Reappraisal of the Temporal Hypothesis, Twenty Years on. *Brain Sciences*, 11(6). <https://doi.org/10.3390/brainsci11060708>
- Hallé, P. A., de Boysson-Bardies, B., & Vihman, M. M. (1991). Beginnings of prosodic organization: Intonation and duration patterns of disyllables produced by Japanese and French infants. *Language and Speech*, 34(Pt 4), 299–318. <https://doi.org/10.1177/002383099103400401>
- Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trends in cognitive sciences*, 5(12), 525-532. [https://doi.org/10.1016/s1364-6613\(00\)01801-5](https://doi.org/10.1016/s1364-6613(00)01801-5)
- Harmony, T. (2013). The functional significance of delta oscillations in cognitive processing. *Frontiers in Integrative Neuroscience*, 7, 83. <https://doi.org/10.3389/fnint.2013.00083>
- Harmony, T., Fernández, T., Silva, J., Bernal, J., Díaz-Comas, L., Reyes, A., Marosi, E., Rodríguez, M., & Rodríguez, M. (1996). EEG delta activity: an indicator of attention to internal processing during performance of mental tasks. *International Journal of Psychophysiology*, 24(1), 161-171. [https://doi.org/https://doi.org/10.1016/S0167-8760\(96\)00053-0](https://doi.org/https://doi.org/10.1016/S0167-8760(96)00053-0)
- Harrison, J. E., Weber, S., Jakob, R., & Chute, C. G. (2021). ICD-11: an international classification of diseases for the twenty-first century. *BMC Medical Informatics and Decision Making*, 21(6), 206. <https://doi.org/10.1186/s12911-021-01534-6>

- Hazra, A., & Gogtay, N. (2016). Biostatistics series module 3: Comparing groups—Numerical variables. *Indian Journal of Dermatology*, 61(3), 251–260. <https://doi.org/10.4103/0019-5154.182416>
- Heim, S., Tschierse, J., Amunts, K., Wilms, M., Vossel, S., Willmes, K., Grabowska, A., & Huber, W. (2008). Cognitive subtypes of dyslexia. *Acta Neurobiologiae Experimentalis*, 68(1), 73–82. <https://doi.org/10.55782/ane-2008-1674>
- Hengeveld, K., & Leufkens, S. (2018). Transparent and non-transparent languages. *Folia Linguistica*, 52, 139-175. <https://doi.org/10.1515/flin-2018-0003>
- Hirsh-Pasek, K., Kemler Nelson, D. G., Jusczyk, P. W., Cassidy, K. W., Druss, B., & Kennedy, L. (1987). Clauses are perceptual units for young infants. *Cognition*, 26(3), 269-286. [https://doi.org/https://doi.org/10.1016/S0010-0277\(87\)80002-1](https://doi.org/https://doi.org/10.1016/S0010-0277(87)80002-1)
- Hoeks, B., & Levelt, W. (1993). Pupillary dilation as a measure of attention: A quantitative system analysis. *Behavior Research Methods, Instruments, & Computers*, 25, 16–26. <https://doi.org/10.3758/BF03204445>
- Huang, J., Gamble, D., Sarnlertsophon, K., Wang, X., & Hsiao, S. (2012). Feeling music: integration of auditory and tactile inputs in musical meter perception. *PLoS One*, 7(10), e48496. <https://doi.org/10.1371/journal.pone.0048496>
- Huettig, F., Lachmann, T., Reis, A., & Petersson, K. M. (2018, 2018/03/16). Distinguishing cause from effect – many deficits associated with developmental dyslexia may be a consequence of reduced and suboptimal reading experience. *Language, Cognition and Neuroscience*, 33(3), 333-350. <https://doi.org/10.1080/23273798.2017.1348528>
- James, A. R. (1988). Marina Nespor & Irene Vogel (1986). Prosodic phonology. Dordrecht: Foris Publications. Pp. xiv + 327. *Phonology*, 5(1), 161-168. <https://doi.org/10.1017/S0952675700002219>
- Jong, P., & Leij, A. (2003). Developmental Changes in the Manifestation of a Phonological Deficit in Dyslexic Children Learning to Read a Regular Orthography. *Journal of educational psychology*, 95, 22-40. <https://doi.org/10.1037/0022-0663.95.1.22>
- Jordan, N. C. (2007). Do words count? Connections between mathematics and reading difficulties. . In D. B. Berch & M. M. M. Mazzocco (Eds.), *Why is math so hard for some children? The nature and origins of mathematical learning difficulties and disabilities* 107-120.
- Joseph, L. M. (2011). Phonological Learning. In S. Goldstein & J. A. Naglieri (Eds.), *Encyclopedia of Child Behavior and Development* (pp. 1095-1097). Springer US. [https://doi.org/10.1007/978-0-387-79061-9\\_2148](https://doi.org/10.1007/978-0-387-79061-9_2148)
- Jusczyk, P. W., Hirsh-Pasek, K., Nelson, D. G., Kennedy, L. J., Woodward, A., & Piwoz, J. (1992). Perception of acoustic correlates of major phrasal units by young infants. *Cognitive Psychology*, 24(2), 252–293. [https://doi.org/10.1016/0010-0285\(92\)90009-Q](https://doi.org/10.1016/0010-0285(92)90009-Q)
- Kemp, K. K. (2007). NEPSY - Second Edition (NEPSY - II) *APA PsycTests*. . <https://doi.org/https://doi.org/10.1037/t15125-000>

- Keshavarzi, M., Mandke, K., Macfarlane, A., Parvez, L., Gabrielczyk, F., Wilson, A., & Goswami, U. (2022). Atypical delta-band phase consistency and atypical preferred phase in children with dyslexia during neural entrainment to rhythmic audio-visual speech. *NeuroImage: Clinical*, 35, 103054. <https://doi.org/10.1016/j.nicl.2022.103054>
- Kinzuka, Y., Minami, T., & Nakauchi, S. (2020). Pupil dilation reflects English /l/r/ discrimination ability for Japanese learners of English: a pilot study. *Scientific Reports*, 10(1), 8052. <https://doi.org/10.1038/s41598-020-65020-1>
- Kitzen, K. R. (2001). Prosodic sensitivity, morphological ability, and reading ability in young adults with and without childhood histories of reading difficulty. *Dissertation Abstracts International Section A: Humanities and Social Sciences*, 62(2-A), 460.
- Knoop-van Campen, C. A. N., Segers, E., & Verhoeven, L. (2018). How phonological awareness mediates the relation between working memory and word reading efficiency in children with dyslexia. *Dyslexia*, 24(2), 156-169. <https://doi.org/https://doi.org/10.1002/dys.1583>
- Kolnes, M., Uusberg, A., & Nieuwenhuis, S. Kolnes, M., Uusberg, A., & Nieuwenhuis, S. (2024). Broadening of attention dilates the pupil. *Attention, Perception, & Psychophysics*, 86(1), 146–158. <https://doi.org/10.3758/s13414-023-02793-3>
- Korn, C. W., Staib, M., Tzovara, A., Castegnetti, G., & Bach, D. R. (2017). A pupil size response model to assess fear learning. *Psychophysiology*, 54(3), 330-343. <https://doi.org/10.1111/psyp.12801>
- Kraus, N., Slater, J., Thompson, E. C., Hornickel, J., Strait, D. L., Nicol, T., & White-Schwoch, T. (2014). Music Enrichment Programs Improve the Neural Encoding of Speech in At-Risk Children. *The Journal of Neuroscience*, 34(36), 11913-11918. <https://doi.org/10.1523/jneurosci.1881-14.2014>
- Kuhl, P., Conboy, B., Padden, D., Nelson, T., & Pruitt, J. (2005). Early Speech Perception and Later Language Development: Implications for the "Critical Period". *Language Learning and Development*, 1, 237-264. [https://doi.org/10.1207/s15473341lld0103&4\\_2](https://doi.org/10.1207/s15473341lld0103&4_2)
- Kuhl, P. K. (2010). Brain mechanisms in early language acquisition. *Neuron*, 67(5), 713-727. <https://doi.org/10.1016/j.neuron.2010.08.038>
- Kuhl, P. K., Williams, K. A., Lacerda, F., Stevens, K. N., & Lindblom, B. (1992, Jan 31). Linguistic experience alters phonetic perception in infants by 6 months of age. *Science*, 255(5044), 606-608. <https://doi.org/10.1126/science.1736364>
- Kuznetsova, A., Brockhoff, P., & Christensen, R. (2017). "lmerTestPackage: Tests in Linear Mixed Effects Models." *Journal of Statistical Software*, 82 (13). <https://doi.org/doi:10.18637/jss.v082.i13> (URL: <https://doi.org/10.18637/jss.v082.i13>).
- Lachmann, T., & Bergström, K. (2023). The multiple-level framework of developmental dyslexia: the long trace from a neurodevelopmental deficit to an impaired cultural technique. *Journal of Cultural Cognitive Science*. <https://doi.org/10.1007/s41809-023-00118-2>

- Ladányi, E., Lukács, Á., & Gervain, J. (2021). Does rhythmic priming improve grammatical processing in Hungarian-speaking children with and without developmental language disorder? *Developmental Science*, *n/a(n/a)*, e13112. <https://doi.org/https://doi.org/10.1111/desc.13112>
- Ladányi, E., Novakovic, M., Boorom, O. A., Aaron, A. S., Scartozzi, A. C., Gustavson, D. E., Nitin, R., Bamikole, P. O., Vaughan, C., Fromboluti, E. K., Schuele, C. M., Camarata, S. M., McAuley, J. D., & Gordon, R. L. (2023). Using Motor Tempi to Understand Rhythm and Grammatical Skills in Developmental Language Disorder and Typical Language Development. *Neurobiology of Language*, *4*(1), 1-28. [https://doi.org/10.1162/nol\\_a\\_00082](https://doi.org/10.1162/nol_a_00082)
- Ladd, D. R., & Arvaniti, A. (2023). Prosodic Prominence Across Languages. *Annual Review of Linguistics*, *9*(Volume 9, 2023), 171-193. <https://doi.org/https://doi.org/10.1146/annurev-linguistics-031120-101954>
- Lallier, M., Tainturier, M. J., Dering, B., Donnadieu, S., Valdois, S., & Thierry, G. (2010). Behavioral and ERP evidence for amodal sluggish attentional shifting in developmental dyslexia. *Neuropsychologia*, *48*(14), 4125-4135. <https://doi.org/10.1016/j.neuropsychologia.2010.09.027>
- Landerl, K., Ramus, F., Moll, K., Lyytinen, H., Leppänen, P. H. T., Lohvansuu, K., O'Donovan, M., Williams, J., Bartling, J., Bruder, J., Kunze, S., Neuhoff, N., Tóth, D., Honbolygó, F., Csépe, V., Bogliotti, C., Iannuzzi, S., Chaix, Y., Démonet, J.-F., Longeras, E., Valdois, S., Chabernaud, C., Delteil-Pinton, F., Billard, C., George, F., Ziegler, J. C., Comte-Gervais, I., Soares-Boucaud, I., Gérard, C.-L., Blomert, L., Vaessen, A., Gerretsen, P., Ekkebus, M., Brandeis, D., Maurer, U., Schulz, E., van der Mark, S., Müller-Myhsok, B., & Schulte-Körne, G. (2013). Predictors of developmental dyslexia in European orthographies with varying complexity. *Journal of Child Psychology and Psychiatry*, *54*(6), 686-694. <https://doi.org/10.1111/jcpp.12029>
- Leben, W. R. (1998). D. Robert Ladd (1996). Intonational phonology. (Cambridge Studies in Linguistics 79.) Cambridge: Cambridge University Press. Pp. xv+334. *Phonology*, *15*(1), 115-118. <https://doi.org/10.1017/S0952675798003546>
- Lee, S., & Lee, D. K. (2018). What is the proper way to apply the multiple comparison test? *Korean Journal of Anesthesiology*, *71*(5), 353–360. <https://doi.org/10.4097/kja.d.18.00242>
- Lenth, R. (2022). *emmeans: Estimated marginal means, aka least-squares means* (R package version 2). <https://CRAN.R-project.org>
- Leong, V., & Goswami, U. (2013). Assessment of Rhythmic Entrainment at Multiple Timescales in Dyslexia : Evidence for Disruption to Syllable Timing. *Hearing research*, *308*. <https://doi.org/10.1016/j.heares.2013.07.015>
- Leong, V., & Goswami, U. (2015). Acoustic-Emergent Phonology in the Amplitude Envelope of Child-Directed Speech. *PLoS One*, *10*(12), e0144411. <https://doi.org/10.1371/journal.pone.0144411>
- Leong, V., Hämäläinen, J., Soltész, F., & Goswami, U. (2011). Rise time perception and detection of syllable stress in adults with developmental dyslexia. *Journal of Memory and Language*, *59*-73. <https://doi.org/10.1016/j.jml.2010.09.003>

- Leong, V., Stone, M. A., Turner, R. E., & Goswami, U. (2014). A role for amplitude modulation phase relationships in speech rhythm perception. *The Journal of the Acoustical Society of America*, 136(1), 366–381. <https://doi.org/10.1121/1.4883366> (2014).
- Levin-Zamir, D., & Bertschi, I. (2018). Media health literacy, eHealth literacy, and the role of the social environment in context. *International Journal of Environmental Research and Public Health*, 15(8), Article 1643. <https://doi.org/10.3390/ijerph15081643>
- Lewandowska, M., Milner, R., Ganc, M., Włodarczyk, E., & Skarżyński, H. (2014). Attention dysfunction subtypes of developmental dyslexia. *Med Sci Monit*, 20, 2256-2268. <https://doi.org/10.12659/msm.890969>
- Liao, H.-I., Kidani, S., Yoneya, M., Kashino, M., & Furukawa, S. (2016). Correspondences among pupillary dilation response, subjective salience of sounds, and loudness. *Psychonomic Bulletin & Review*, 23(2), 412-425. <https://doi.org/10.3758/s13423-015-0898-0>
- Lisker, & Abramson. (1967). Some Effects of Context On Voice Onset Time in English Stops. *Language and Speech*, 10(1), 1-28. <https://doi.org/10.1177/002383096701000101>
- Lisker, L. (1977). Rapid versus rabid: A catalogue of acoustic features that may cue the distinction. *The Journal of the Acoustical Society of America*, 62(4), 961–967. <https://doi.org/10.1121/1.381600>
- Lisker, L., & Abramson, A. S. (1964). A Cross-Language Study of Voicing in Initial Stops: Acoustical Measurements. *WORD*, 20(3), 384-422. <https://doi.org/10.1080/00437956.1964.11659830>
- Lleo, C., & Demuth, K. (1999). Prosodic Constraints on the Emergence of Grammatical Morphemes: Crosslinguistic Evidence from Germanic and Romance Languages. *Proceedings of the 23rd Annual Boston University Conference on Language Development*.
- Lorusso, M. L., & Toraldo, A. (2023). Revisiting Multifactor Models of Dyslexia: Do They Fit Empirical Data and What Are Their Implications for Intervention? *Brain Sciences*, 13(2), 328. <https://www.mdpi.com/2076-3425/13/2/328>
- Lou, C., Duan, X., Altarelli, I., Sweeney, J. A., Ramus, F., & Zhao, J. (2019). White matter network connectivity deficits in developmental dyslexia. *Human Brain Mapping*, 40(2), 505-516. <https://doi.org/10.1002/hbm.24390>
- Lukov, L., Friedmann, N., Shalev, L., Khentov-Kraus, L., Shalev, N., Lorber, R., & Guggenheim, R. (2015). Dissociations between developmental dyslexias and attention deficits *Frontiers in Psychology*, 8. <https://doi.org/10.3389/fpsyg.2014.01501>
- Luna-Rodriguez, A., Wendt, M., Kerner auch Koerner, J., Gawrilow, C., & Jacobsen, T. (2018, 2018/11/10). Selective impairment of attentional set shifting in adults with ADHD. *Behavioral and Brain Functions*, 14(1), 18. <https://doi.org/10.1186/s12993-018-0150-y>
- Maassen, B., Groenen, P., Crul, T., Assman-Hulsmans, C., & Gabreels, F. (2001). Identification and discrimination of voicing and place-of-articulation in developmental dyslexia. *Clinical Linguistics & Phonetics*, 15, 319-339.

- MacLeod, B. (2015). A critical evaluation of two approaches to defining perceptual salience. *Ampersand*, 2, 83-92. <https://doi.org/https://doi.org/10.1016/j.amper.2015.07.001>
- Macmillan, N., & Creelman, D. (2004). *Detection Theory: A User's Guide* (Vol. xix). <https://doi.org/10.4324/9781410611147>
- Mairano, P., & De Iacovo, V. (2020, Sep). Gemination in Northern versus Central and Southern Varieties of Italian: A Corpus-based Investigation. *Language and Speech*, 63(3), 608-634. <https://doi.org/10.1177/0023830919875481>
- Makowski. (2018). The Psycho Package: An Efficient and Publishing-Oriented Workflow for Psychological Science. *Journal of Open Source Software*, 3(22). <https://doi.org/Available> from <https://github.com/neuropsychology/psycho.R>
- Mampe, B., Friederici, A. D., Christophe, A., & Wermke, K. (2009). Newborns' cry melody is shaped by their native language. *Current Biology*, 19(23), 1994-1997. <https://doi.org/10.1016/j.cub.2009.09.064>
- Marchetti, R., Pinto, S., Spieser, L., Vaugoyeau, M., Cavalli, E., El Ahmadi, A., Assaiante, C., & Colé, P. (2023). Phoneme Representation and Articulatory Impairment: Insights from Adults with Comorbid Motor Coordination Disorder and Dyslexia. *Brain Science*, 13(2). <https://doi.org/10.3390/brainsci13020210>
- Marini, F., Chelazzi, L., & Maravita, A. (2013). The costly filtering of potential distraction: evidence for a supramodal mechanism. *Journal of Experimental Psychology: General*, 142(3), 906-922. <https://doi.org/10.1037/a0029905>
- Marini, F., Demeter, E., Roberts, K. C., Chelazzi, L., & Woldorff, M. G. (2016). Orchestrating Proactive and Reactive Mechanisms for Filtering Distracting Information: Brain-Behavior Relationships Revealed by a Mixed-Design fMRI Study. *Journal of Neuroscience*, 36(3), 988-1000. <https://doi.org/10.1523/jneurosci.2966-15.2016>
- Martin, A., Kronbichler, M., & Richlan, F. (2016, Jul). Dyslexic brain activation abnormalities in deep and shallow orthographies: A meta-analysis of 28 functional neuroimaging studies. *Human Brain Mapping*, 37(7), 2676-2699. <https://doi.org/10.1002/hbm.23202>
- Mary Zarate, J., Ritson, C. R., & Poeppel, D. (2012). Pitch-interval discrimination and musical expertise: is the semitone a perceptual boundary? *The Journal of the Acoustical Society of America*, 132(2), 984-993. <https://doi.org/10.1121/1.4733535>
- Masonheimer, P. E., Drum, P. A., & Ehri, L. C. (1984). Does Environmental Print Identification Lead Children into Word Reading? *Journal of Reading Behavior*, 16(4), 257-271. <https://doi.org/10.1080/10862968409547520>
- Masoura, E., Gogou, A., & Gathercole, S. E. (2021). Working memory profiles of children with reading difficulties who are learning to read in Greek. *Dyslexia*, 27(3), 312-324. <https://doi.org/10.1002/dys.1671>

- Masterson, J., Hazan, V., & Wijayatilake, L. (1995). Masterson, J., Hazan, V., & Wijayatilake, L. (1995). Phonemic processing problems in developmental phonological dyslexia. *Cognitive Neuropsychology*, *12*(2), 233–259. <https://doi.org/10.1080/02643299508251997>
- Matarazzo, J. D. (1972). *Wechsler's measurement and appraisal of adult intelligence*. Baltimore, MD: The Williams & Wilkins Company. Wechsler's measurement and appraisal of adult intelligence. . *Baltimore, MD: The Williams & Wilkins Company*.
- Mathôt, S. (2018). Pupillometry: Psychology, physiology, and function. *Journal of Cognition*, *1*(1), 16. <https://doi.org/10.5334/joc.18>
- Mathôt, S., & Vilotijević, A. (2023). Methods in cognitive pupillometry: Design, preprocessing, and statistical analysis. *Behavior Research Methods*, *55*(6), 3055–3077. <https://doi.org/10.3758/s13428-022-01957-7>
- Mattys, & Samuel. (1997). How Lexical Stress Affects Speech Segmentation and Interactivity: Evidence from the Migration Paradigm. *Journal of Memory and Language*, *36*(1), 87-116. <https://doi.org/https://doi.org/10.1006/jmla.1996.2472>
- Matzinger, Ritt, & Fitch. (2021). The Influence of Different Prosodic Cues on Word Segmentation. *Frontiers in Psychology*, *12*. <https://doi.org/10.3389/fpsyg.2021.622042>
- McArthur, G. M., Hogben, J. H., Edwards, V. T., Heath, S. M., & Mengler, E. D. (2000). On the specifics of specific reading disability and specific language impairment. *Journal of Child Psychology and Psychiatry*, *41*(7), 869-874. <https://doi.org/10.1017/S0021963099006186>
- McMurray, B., Clayards, M. A., Tanenhaus, M. K., & Aslin, R. N. (2008). Tracking the time course of phonetic cue integration during spoken word recognition. *Psychonomic Bulletin & Review*, *15*(6), 1064–1071. <https://doi.org/10.3758/pbr.15.6.1064T>
- McNeill, B., Gillon, G., Gath, M., & Woodward, L. (2025). Trajectories of language development, cognitive flexibility and phoneme awareness knowledge in early childhood. *International Journal of Language & Communication Disorders*, *60*(1), e13139. <https://doi.org/10.1111/1460-6984.13139>
- Meissner, S. N., Bächinger, M., Kikkert, S., Imhof, J., Missura, S., Carro Dominguez, M., & Wenderoth, N. (2024). Self-regulating arousal via pupil-based biofeedback. *Nature Human Behaviour*, *8*(1), 43-62. <https://doi.org/10.1038/s41562-023-01729-z>
- Meixner, J. M., Warner, G. J., Lensing, N., Schiefele, U., & Elsner, B. (2019). The relation between executive functions and reading comprehension in primary-school students: A cross-lagged-panel analysis. *Early Childhood Research Quarterly*, *46*, 62-74. <https://doi.org/https://doi.org/10.1016/j.ecresq.2018.04.010>
- Melby-Lervåg, M., Lyster, S. A. H., & Hulme, C. (2012). Phonological skills and their role in learning to read: A meta-analytic review. *Psychological Bulletin*, *138*(2), 322–352. <https://doi.org/10.1037/a0026744>
- Mendonça, A. G., Drugowitsch, J., Vicente, M. I., DeWitt, E. E. J., Pouget, A., & Mainen, Z. F. (2020). The impact of learning on perceptual decisions and its implication for speed-

accuracy tradeoffs. *Nature Communications*, 11(1), 2757. <https://doi.org/10.1038/s41467-020-16196-7>

- Menghini, D., Finzi, A., Benassi, M., Bolzani, R., Facoetti, A., Giovagnoli, S., Ruffino, M., & Vicari, S. (2010). Different underlying neurocognitive deficits in developmental dyslexia: a comparative study. *Neuropsychologia*, 48(4), 863-872. <https://doi.org/10.1016/j.neuropsychologia.2009.11.003>
- Menghini, D., Finzi, A., Carlesimo, G. A., & Vicari, S. (2011). Working Memory Impairment in Children With Developmental Dyslexia: Is it Just a Phonological Deficity? *Developmental neuropsychology*, 36(2), 199-213. <https://doi.org/10.1080/87565641.2010.549868>
- Midway, S., Robertson, M., Flinn, S., & Kaller, M. (2020). Comparing multiple comparisons: practical guidance for choosing the best multiple comparisons test. *PeerJ*, 8, e10387. <https://doi.org/10.7717/peerj.10387>
- Miendlarzewska, E., & Trost, W. (2014). How musical training affects cognitive development: rhythm, reward and other modulating variables. *Frontiers in Neuroscience*, 7. <https://doi.org/10.3389/fnins.2013.00279>
- Milankov, V., Golubović, S., Krstić, T., & Golubović, Š. (2021). Phonological awareness as the foundation of reading acquisition in students reading in transparent orthography. *International Journal of Environmental Research and Public Health*, 18(10), Article 5440. <https://doi.org/10.3390/ijerph18105440>
- Miles, T. R. (2004). Some Problems in Determining the Prevalence of Dyslexia. *Revista electrónica de investigación psicoeducativa y psicopedagógica*, 2(2), 5. <https://go.exlibris.link/98xgcCWj>
- Mina, F., Darweesh, M. E. S., Khattab, A. N., & Serag, S. M. (2021). Role and efficacy of music therapy in learning disability: a systematic review. *The Egyptian Journal of Otolaryngology*, 37(1), 31. <https://doi.org/10.1186/s43163-021-00091-z>
- Mori, Y., Erickson, D., Rilliard, A., & Hori, T. (2014, 08/01). Effects of Vowel Duration, Intensity, and Articulation Rate on Judgments of Naturalness and Intelligibility of Japanese Learners' English. *Journal of the Phonetic Society of Japan*, 18, 30-41.
- Mousikou, P., Strycharczuk, P., & Rastle, K. (2024). Acoustic correlates of stress in speech perception. *Journal of Memory and Language*, 136, 104509. <https://doi.org/10.1016/j.jml.2024.104509>
- Mundy, I. R., & Carroll, J. M. (2013). Spelling-stress regularity effects are intact in developmental dyslexia. *Quarterly Journal of Experimental Psychology*, 66(4), 816–828. <https://doi.org/10.1080/17470218.2012.719530>
- Mundy, I. R., & Wood, C. (2024). Prosody and developmental dyslexia: A meta-analysis. *Reading and Writing*. <https://doi.org/10.1007/s11145-024-10610-y>
- Muneaux, M., Ziegler, J. C., Truc, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: evidence from French. *NeuroReport*, 15(8), 1255-1259. <https://doi.org/10.1097/01.wnr.0000127459.31232.c4>

- Narhi-Martinez, W., Dube, B., & Golomb, J. D. (2023). Attention as a multi-level system of weights and balances. *Wiley Interdisciplinary Reviews: Cognitive Science*, 14(1), e1633. <https://doi.org/10.1002/wcs.1633>
- Natick. (2022). *MATLAB version: 9.13.0 (R2022b)*. In The MathWorks Inc. <https://www.mathworks.com>
- Nicolson, R. I., & Fawcett, A. J. (1994). Reaction times and dyslexia. *Quarterly Journal of Experimental Psychology Section A*, 47(1), 29–48. <https://doi.org/10.1080/14640749408401142>
- Noble, K. G., Farah, M. J., & McCandliss, B. D. (2006). Socioeconomic background modulates cognition-achievement relationships in reading. *Cognitive Development*, 21(3), 349–368. <https://doi.org/10.1016/j.cogdev.2006.01.007>
- Noonan, M. P., Crittenden, B. M., Jensen, O., & Stokes, M. G. (2018). Selective inhibition of distracting input. *Behavioural Brain Research*, 355, 36-47. <https://doi.org/https://doi.org/10.1016/j.bbr.2017.10.010>
- Noordenbos, M., & Serniclaes, W. (2015). The Categorical Perception Deficit in Dyslexia: A Meta-Analysis. *Scientific Studies of Reading*, 1-20. <https://doi.org/10.1080/10888438.2015.1052455>
- O'Brien, G. E., Gijbels, L., & Yeatman, J. D. (2020). Context effects on phoneme categorization in children with dyslexia. *The Journal of the Acoustical Society of America*, 148(4), 2209. <https://doi.org/10.1121/10.0002181>
- Orcutt, G. H., Watts, H. W., & Edwards, J. B. (1968). Data aggregation and information loss. *The American Economic Review*, 58(4), 773–787. <http://www.jstor.org/stable/1815532>
- Orsini, P., & Picone, L. (2012). *WISC-IV: Contributo alla taratura italiana* (4th ed.). Giunti OS.
- Ortiz-Mantilla, S., Choudhury, N., Alvarez, B., & Benasich, A. A. (2010). Involuntary switching of attention mediates differences in event-related responses to complex tones between early and late Spanish–English bilinguals. *Brain Research*, 1362, 78-92. <https://doi.org/https://doi.org/10.1016/j.brainres.2010.09.031>
- Pasquini, E., Corriveau, K., & Goswami, U. (2007). Auditory Processing of Amplitude Envelope Rise Time in Adults Diagnosed With Developmental Dyslexia. *Scientific Studies of Reading*, 11, 259-286. <https://doi.org/10.1080/10888430701344280>
- Paulesu, E., Frith, U., Snowling, M., Gallagher, A., Morton, J., Frackowiak, R. S. J., & Frith, C. D. (1996). Is developmental dyslexia a disconnection syndrome?: Evidence from PET scanning. *Brain*, 119(1), 143-157. <https://doi.org/10.1093/brain/119.1.143>
- Peirce, J. W., Gray, J. R., Simpson, S., MacAskill, M. R., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, 51(1), 195–203. <https://doi.org/10.3758/s13428-018-01193-yP>

- Pennington, B. F. (2006). From single to multiple deficit models of developmental disorders. *Cognition*, 101(2), 385-413. <https://doi.org/10.1016/j.cognition.2006.04.008>
- Piazza, E. A., Jordan, M. C., & Lew-Williams, C. (2017). Mothers Consistently Alter Their Unique Vocal Fingerprints When Communicating with Infants. *Current Biology*, 27(20), 3162-3167.e3163. <https://doi.org/10.1016/j.cub.2017.08.074>
- Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W., Humes, L. E., Lemke, U., Lunner, T., Matthen, M., Mackersie, C. L., Naylor, G., Phillips, N. A., Richter, M., Rudner, M., Sommers, M. S., Tremblay, K. L., & Wingfield, A. (2016). Hearing Impairment and Cognitive Energy: The Framework for Understanding Effortful Listening (FUEL). *Ear and Hearing*, 37 Suppl 1, 5s-27s. <https://doi.org/10.1097/aud.0000000000000312>
- Piquado, T., Isaacowitz, D., & Wingfield, A. (2010). Pupillometry as a measure of cognitive effort in younger and older adults. *Psychophysiology*, 47(3), 560-569. <https://doi.org/10.1111/j.1469-8986.2009.00947.x>
- Plag, I., Kunter, G., & Schramm, M. (2011). Acoustic correlates of primary and secondary stress in North American English. *Journal of Phonetics*, 39(3), 362-374. <https://doi.org/https://doi.org/10.1016/j.wocn.2011.03.004>
- Poeppel, D., & Assaneo, M. F. (2020). Speech rhythms and their neural foundations. *Nature Reviews Neuroscience*, 21(6), 322-334. <https://doi.org/10.1038/s41583-020-0304-4>
- Potier Watkins, C., Dehaene, S., & Friedmann, N. (2023). Characterizing different types of developmental dyslexias in French: The Malabi screener. *Cognitive Neuropsychology*, 40(7-8), 319-350. <https://doi.org/10.1080/02643294.2024.2327665>
- Price, C. J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage*, 62(2), 816-847. <https://doi.org/10.1016/j.neuroimage.2012.04.062>
- Protopapa, C., & Smith-Spark, J. H. (2022). Self-reported symptoms of developmental dyslexia predict impairments in everyday cognition in adults. *Research in developmental disabilities*, 128, 104288. <https://doi.org/https://doi.org/10.1016/j.ridd.2022.104288>
- Protopapas, A. (2014). From temporal processing to developmental language disorders: mind the gap. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 369(1634), 20130090. <https://doi.org/10.1098/rstb.2013.0090>
- Quam, C., & Swingle, D. (2014). Processing of lexical stress cues by young children. *Journal of Experimental Child Psychology*, 123, 73-89. <https://doi.org/10.1016/j.jecp.2014.01.010>
- Quené, H. (2022). *hqmisc: Miscellaneous convenience functions and dataset* (R package version 0.2-1) [Computer software]. <https://CRAN.R-project.org/package=hqmisc>
- R Core Team. (2022). *R: A language and environment for statistical computing*. In R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.

- Raghuram, A., Gowrisankaran, S., Swanson, E., Zurakowski, D., Hunter, D. G., & Waber, D. P. (2018). Frequency of Visual Deficits in Children With Developmental Dyslexia. *JAMA Ophthalmol*, 136(10), 1089-1095. <https://doi.org/10.1001/jamaophthalmol.2018.2797>
- Ramus, F., & Ahissar, M. (2012). Developmental dyslexia: The difficulties of interpreting poor performance, and the importance of normal performance. *Cognitive neuropsychology*, 29(1-2), 104-122. <https://doi.org/10.1080/02643294.2012.677420>
- Ramus, F., Marshall, C. R., Rosen, S., & van der Lely, H. K. J. (2013). Phonological deficits in specific language impairment and developmental dyslexia: towards a multidimensional model. *Brain: a journal of neurology*, 136(Pt 2), 630-645. <https://doi.org/10.1093/brain/aws356>
- Ramus, F., Pidgeon, E., & Frith, U. (2003). The relationship between motor control and phonology in dyslexic children. *Journal of Child Psychology and Psychiatry*, 44(5), 712-722. <https://doi.org/10.1111/1469-7610.00157>
- Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. *Brain (London, England : 1878)*, 126(4), 841-865. <https://doi.org/10.1093/brain/awg076>
- Ramus, F., & Szenkovits, G. (2008). What Phonological Deficit? *Quarterly Journal of Experimental Psychology*, 61(1), 129-141. <https://doi.org/10.1080/17470210701508822>
- Rathcke, & Lin. (2021, Sep 30). Towards a Comprehensive Account of Rhythm Processing Issues in Developmental Dyslexia. *Brain Sciences*, 11(10). <https://doi.org/10.3390/brainsci11101303>
- Rathcke, T., & Lin, C.-Y. (2021). Towards a Comprehensive Account of Rhythm Processing Issues in Developmental Dyslexia. *Brain Sciences*, 11(10), 1303. <https://doi.org/10.3390/brainsci11101303>
- Rathcke, T., Lin, C.-Y., Falk, S., & Dalla Bella, S. (2021). Tapping into linguistic rhythm. *Laboratory Phonology: Journal of the Association for Laboratory Phonology*, 12(1):11, 1-32. <https://doi.org/10.5334/labphon.248>
- Rathcke, T., Lin, C.-Y., Smit, E., & Frassinelli, D. (2024). Taken by Surprisal? On the Role of Linguistic Predictability in Speech Rhythm. <https://doi.org/10.21437/SpeechProsody.2024-30>
- Rathcke, T., & Smith, R. (2015). Speech timing and linguistic rhythm: On the acoustic bases of rhythm typologies. *The Journal of the Acoustical Society of America*, 137, 2834. <https://doi.org/10.1121/1.4919322>
- Raven, J., Court, J. H., & Raven, J. C. (1998). *Raven Manual*. Oxford, UK: Oxford Psychologist Press.
- RCoreTeam. (2022). *R: A language and environment for statistical computing*. <https://www.R-project.org/>.

- Reid, A. A., Szczerbinski, M., Iskierka-Kasperek, E., & Hansen, P. (2007). Cognitive profiles of adult developmental dyslexics: theoretical implications. *Dyslexia*, *13*(1), 1-24. <https://doi.org/10.1002/dys.321>
- Reis, S. M., McGuire, J. M., & Neu, T. W. (2000). Compensation Strategies Used by High-Ability Students With Learning Disabilities who Succeed In College. *Gifted Child Quarterly*, *44*(2), 123-134. <https://doi.org/10.1177/001698620004400205>
- Revelle, W. (2024). psychTools: Tools to Accompany the 'psych' Package for Psychological Research. *Evanston*. <https://doi.org/> <https://CRAN.R-project.org/package=psychTools>.
- Richards, & Goswami. (2015). Auditory Processing in Specific Language Impairment (SLI): Relations With the Perception of Lexical and Phrasal Stress. *Journal of Speech, Language, and Hearing Research*, *58*(4), 1292-1305. [https://doi.org/10.1044/2015\\_JSLHR-L-13-0306](https://doi.org/10.1044/2015_JSLHR-L-13-0306)
- Richards, & Goswami. (2019). Impaired Recognition of Metrical and Syntactic Boundaries in Children with Developmental Language Disorders. *Brain Sciences*, *9*(2). <https://doi.org/10.3390/brainsci9020033>
- Roberts, G., Rane, S., Fall, A. M., Denton, C. A., Fletcher, J. M., & Vaughn, S. (2015). The Impact of Intensive Reading Intervention on Level of Attention in Middle School Students. *Journal of Clinical Child and Adolescent Psychology*, *44*(6), 942-953. <https://doi.org/10.1080/15374416.2014.913251>
- Robison, M. K., & Unsworth, N. (2019). Pupillometry tracks fluctuations in working memory performance. *Attention, Perception, & Psychophysics*, *81*(2), 407-419. <https://doi.org/10.3758/s13414-018-1618-4>
- Rossi, M. R., Smit, E., Van der Werff, J., Ravignani, A., & Rathcke, T. (2024). Testing Rhythmic Abilities in Developmental Dyslexia: Is Internal Rhythm Generation Intact? *Music Perception*.
- RStudio, T. (2022). RStudio: Integrated Development Environment for R. *RStudio, PBC*. <https://doi.org/http://www.rstudio.com/>.
- Sabri, M., Humphries, C., Verber, M., Liebenthal, E., Binder, J. R., Mangalathu, J., & Desai, A. (2014). Neural effects of cognitive control load on auditory selective attention. *Neuropsychologia*, *61*, 269-279. <https://doi.org/10.1016/j.neuropsychologia.2014.06.009>
- Sadusky, A., Berger, E. P., Reupert, A. E., & Freeman, N. C. (2022, May). Methods used by psychologists for identifying dyslexia: A systematic review. *Dyslexia*, *28*(2), 132-148. <https://doi.org/10.1002/dys.1706>
- Sato, Y., Kato, M., & Mazuka, R. (2012). Development of single/geminate obstruent discrimination by Japanese infants: Early integration of durational and nondurational cues. *Developmental Psychology*, *48*(1), 18–34. <https://doi.org/10.1037/a0025528>
- Schild, U., Becker, A. B., & Friedrich, C. K. (2014). Processing of syllable stress is functionally different from phoneme processing and does not profit from literacy acquisition. *Frontiers in Psychology*, *5*, 530. <https://doi.org/10.3389/fpsyg.2014.00530>

- Schwarz, J., Lizarazu, M., Lallier, M., & Klimovich-Gray, A. (2024). Phonological deficits in dyslexia impede lexical processing of spoken words: Linking behavioural and MEG data. *Cortex*, 171, 204-222. <https://doi.org/https://doi.org/10.1016/j.cortex.2023.10.003>
- Senkal, O. A., & Muhtar, Z. (2021). Role of orff music therapy in improving auditory processing skills in children with intellectual disability. *Nigerian Journal of Clinical Practice*, 24(7), 1005-1014. [https://doi.org/10.4103/njcp.njcp\\_410\\_20](https://doi.org/10.4103/njcp.njcp_410_20)
- Serniclaes, W., Sprenger-Charolles, L., Carré, R., & Demonet, J. (2001). Perceptual Discrimination of Speech Sounds in Developmental Dyslexia. *Journal of speech, language, and hearing research : JSLHR*, 44, 384-399. [https://doi.org/10.1044/1092-4388\(2001\)032](https://doi.org/10.1044/1092-4388(2001)032)
- Serniclaes, W., Van Heghe, S., Mousty, P., Carré, R., & Sprenger-Charolles, L. (2004). Allophonic mode of speech perception in dyslexia. *Journal of Experimental Child Psychology*, 87(4), 336–361. <https://doi.org/10.1016/j.jecp.2004.02.001>
- Seymour, P. H., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology*, 94(Pt 2), 143–174. <https://doi.org/10.1348/000712603321661859>
- Share, D. L. (1995). Phonological recoding and self-teaching: sine qua non of reading acquisition. *Cognition*, 55(2), 151-218; discussion 219-126. [https://doi.org/10.1016/0010-0277\(94\)00645-2](https://doi.org/10.1016/0010-0277(94)00645-2)
- Share, D. L. (2008). On the Anglocentricities of current reading research and practice: The perils of overreliance on an "outlier" orthography. *Psychological Bulletin*, 134(4), 584–615. <https://doi.org/10.1037/0033-2909.134.4.584>
- Singh, L., Morgan, J. L., & Best, C. T. (2002). Infants' Listening Preferences: Baby Talk or Happy Talk? *Infancy*, 3(3), 365-394. [https://doi.org/https://doi.org/10.1207/S15327078IN0303\\_5](https://doi.org/https://doi.org/10.1207/S15327078IN0303_5)
- Siok, W. T., & Fletcher, P. (2001). The role of phonological awareness and visual-orthographic skills in Chinese reading acquisition Developmental Psychology. *Developmental Psychology*, 37, 886-899. <https://doi.org/10.1037//0012-1649.37.6.886>
- Smith, & Rathcke. (2017). Glasgow Gloom or Leeds Glue? Dialect-Specific Vowel Duration Constrains Lexical Segmentation and Access. *Phonetica*, 74(1), 1-24. <https://doi.org/10.1159/000444857>
- Smith-Spark, J. H., Gordon, R., & Jansari, A. S. (2023). The impact of developmental dyslexia on workplace cognition: evidence from a virtual reality environment. *Behaviour & Information Technology*, 42(3), 269-277. <https://doi.org/10.1080/0144929X.2022.2152367>
- Snow, D., & Balog, H. L. (2002). Do children produce the melody before the words? A review of developmental intonation research. *Lingua*, 112(12), 1025-1058. [https://doi.org/https://doi.org/10.1016/S0024-3841\(02\)00060-8](https://doi.org/https://doi.org/10.1016/S0024-3841(02)00060-8)
- Snowling, M. (1995). Phonological processing and developmental dyslexia. *Journal of Research in Reading*, 18(2), 132-138. <https://doi.org/https://doi.org/10.1111/j.1467-9817.1995.tb00079.x>

- Snowling, M. (2003). Dyslexia as a Phonological Deficit: Evidence and Implications. *Child and Adolescent Mental Health*, 3, 4-11. <https://doi.org/10.1111/1475-3588.00201>
- Sofologi, M., Papatzikis, E., Kougioumtzis, G., Kosmidou, E., Klitsioti, A., Droutme, A., Sourbi, A.-A., Chrisostomou, D., & Efstratopoulou, M. (2022). Effectiveness of Musical Training on Reading Comprehension in Elementary School Children. Is There an Associative Cognitive Benefit? *Frontiers in Education*, 7. <https://doi.org/10.3389/feduc.2022.875511>
- Sóskuthy, M. (2021). Evaluating generalised additive mixed modelling strategies for dynamic speech analysis. *Journal of Phonetics*, 84, 101017. <https://doi.org/10.1016/j.wocn.2020.101017>
- Sprenger-Charolles, L., Colé, P., Piquard, A., Pinton, F., & Billard, C. (2009). Reliability and prevalence of an atypical development of phonological skills in French-speaking dyslexics. *Reading and Writing*, 22, 811-842. <https://doi.org/10.1007/s11145-008-9117-y>
- Stanovich, K. (2017). Speculations on the causes and consequences of individual differences in early reading acquisition. *Reading acquisition* (pp. 307–342). <https://doi.org/10.4324/9781351236904-11>
- Sutherland, D., & Gillon, G. T. (2007). Development of phonological representations and phonological awareness in children with speech impairment. *International Journal of Language & Communication Disorders*, 42(2), 229–250. <https://doi.org/10.1080/13682820600806672>
- Tal, D., & Shaul, S. (2024). The role of cognitive flexibility in emergent literacy. *Journal of Applied Developmental Psychology*, 94, 101692. <https://doi.org/https://doi.org/10.1016/j.appdev.2024.101692>
- Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and language*, 9(2), 182-198. [https://doi.org/10.1016/0093-934x\(80\)90139-x](https://doi.org/10.1016/0093-934x(80)90139-x)
- Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education*, 2, 53-55. <https://doi.org/10.5116/ijme.4dfb.8dfd>
- Teki, S., Grube, M., & Griffiths, T. (2012). A Unified Model of Time Perception Accounts for Duration-Based and Beat-Based Timing Mechanisms. *Frontiers in Integrative Neuroscience*, 5. <https://doi.org/10.3389/fnint.2011.00090>
- Tekin, K., Sekeroglu, M. A., Kiziltoprak, H., Doguizi, S., Inanc, M., & Yilmazbas, P. (2018). Static and dynamic pupillometry data of healthy individuals. *Clinical and Experimental Optometry*, 101(5), 659–665. <https://doi.org/10.1111/exo.12659>
- Thomas, K. E., & König, C. J. (2018). Knowledge of Previous Tasks: Task Similarity Influences Bias in Task Duration Predictions. *Frontiers in Psychology*, 9. <https://doi.org/10.3389/fpsyg.2018.00760>
- Thomson, J. M., & Goswami, U. (2008). Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *Journal of Physiology-Paris*, 102(1–3), 120–129. <https://doi.org/10.1016/j.jphysparis.2008.03.007>

- Thomson, J. M., & Goswami, U. (2010). Learning novel phonological representations in developmental dyslexia: associations with basic auditory processing of rise time and phonological awareness. *Reading and Writing, 23*, 453-473.
- Tierney, A. T., & Kraus, N. (2013). The ability to tap to a beat relates to cognitive, linguistic, and perceptual skills. *Brain and language, 124*(3), 225-231.  
<https://doi.org/10.1016/j.bandl.2012.12.014>
- Tilanus, E. A., Segers, E., & Verhoeven, L. (2013). Diagnostic profiles of children with developmental dyslexia in a transparent orthography. *Research in Developmental Disabilities, 34*(11), 4194–4202. <https://doi.org/10.1016/j.ridd.2013.08.039>
- TobiiAB. (2022a). *Tobii Pro Glasses 3. User Manual*. <https://doi.org/> <https://go.tobii.com/tobii-pro-glasses-3-user-manual>
- TobiiAB. (2022b). Tobii Pro Glasses 3 data quality test report: Accuracy, precision, and data loss under controlled environment (Rev. 1).
- Tomas, D., & Smith-Lock, P. (2015). Phonological and morphophonological effects on grammatical development in children with specific language impairment. *International Journal of Language & Communication Disorders, 50*(4), 516–528. <https://doi.org/10.1111/1460-6984.12152>
- Tonér, S., Kallioinen, P., & Lacerda, F. (2021, 2021-May-17). Selective Auditory Attention Associated With Language Skills but Not With Executive Functions in Swedish Preschoolers. *Frontiers in Psychology, 12*. <https://doi.org/10.3389/fpsyg.2021.664501>
- Tops, W., Callens, M., Stevens, M., & Brysbaert, M. (2021). *Students with dyslexia in higher education: Academic performance and predictors for success*. <https://doi.org/10.13140/RG.2.2.30950.96329>
- Treiman, R., & Zukowski, A. (1991). Levels of phonological awareness. In S. A. Brady & D. P. Shankweiler (Eds.), *Phonological processes in literacy: A tribute to Isabelle Y. Liberman* (pp. 67–83). Lawrence Erlbaum Associates.
- Urgesi, C., Campanella, F., & Fabbro, F. (2011). *NEPSY-2: Contributo alla taratura italiana* (2nd ed.). Giunti O.S.
- Valdois, S. (2022). The visual-attention span deficit in developmental dyslexia: Review of evidence for a visual-attention-based deficit. *Dyslexia, 28*(4), 397-415.  
<https://doi.org/10.1002/dys.1724>
- van Bergen, E., van der Leij, A., & de Jong, P. F. (2014). The intergenerational multiple deficit model and the case of dyslexia. *Frontiers in Human Neuroscience, 8*, 346.  
<https://doi.org/10.3389/fnhum.2014.00346>
- van Viersen, S., de Bree, E. H., & de Jong, P. F. (2019). Protective Factors and Compensation in Resolving Dyslexia. *Scientific Studies of Reading, 23*(6), 461-477.  
<https://doi.org/10.1080/10888438.2019.1603543>

- Vandermosten, M., Boets, B., Luts, H., Poelmans, H., Golestani, N., Wouters, J., & Ghesquière, P. (2010). Adults with dyslexia are impaired in categorizing speech and nonspeech sounds on the basis of temporal cues. *Proceedings of the National Academy of Sciences of the United States of America*, *107*, 10389-10394. <https://doi.org/10.1073/pnas.0912858107>
- Vandermosten, M., Correia, J., Vanderauwera, J., Wouters, J., Ghesquière, P., & Bonte, M. (2020). Brain activity patterns of phonemic representations are atypical in beginning readers with family risk for dyslexia. *Developmental Science*, *23*(1), e12857. <https://doi.org/10.1111/desc.12857>
- Vanelli, M. (Ed.). (2021). *Fonologia e prosodia dell'italiano* Carocci.
- 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>
- Vierra, A., Razzaq, A., & Andreadis, A. (2023). Chapter 27 - Continuous variable analyses: t-test, Mann–Whitney U, Wilcoxon sign rank. In A. E. M. Eltorai, J. A. Bakal, P. C. Newell, & A. J. Osband (Eds.), *Translational Surgery* (pp. 165-170). Academic Press. <https://doi.org/https://doi.org/10.1016/B978-0-323-90300-4.00045-8>
- Virtala, P., Talola, S., Partanen, E., & Kujala, T. (2020). Poor neural and perceptual phoneme discrimination during acoustic variation in dyslexia. *Scientific Reports*, *10*(1), 8646. <https://doi.org/10.1038/s41598-020-65490-3>
- Wade-Woolley, L., Wood, C., Chan, J., & Weidman, S. (2021). Prosodic Competence as the Missing Component of Reading Processes Across Languages: Theory, Evidence and Future Research. *Scientific Studies of Reading*. <https://doi.org/10.1080/10888438.2021.1995390>!
- Wade-Woolley, L., Wood, C., Chan, J., & Weidman, S. (2022). Prosodic Competence as the Missing Component of Reading Processes Across Languages: Theory, Evidence and Future Research. *Scientific Studies of Reading*, *26*(2), 165-181. <https://doi.org/10.1080/10888438.2021.1995390>
- Wager, T. D., Jonides, J., & Smith, E. E. (2006 ). Individual differences in multiple types of shifting attention. *Memory & Cognition*, *34*, 1730–1743 <https://doi.org/https://doi.org/10.3758/BF03195934>
- Wagner, & Watson. (2010). Experimental and theoretical advances in prosody: A review. *Language and cognitive processes*, *25*(7-9), 905-945. <https://doi.org/10.1080/01690961003589492>
- Wagner, R., & Torgesen, J. (1987). The Nature of Phonological Processing and Its Causal Role in the Acquisition of Reading Skills. *Psychological bulletin*, *101*, 192-212. <https://doi.org/10.1037/0033-2909.101.2.192>
- Wagner, R. K., Zirps, F. A., Edwards, A. A., Wood, S. G., Joyner, R. E., Becker, B. J., Liu, G., & Beal, B. (2020). The Prevalence of Dyslexia: A New Approach to Its Estimation. *Journal of learning disabilities*, *53*(5), 354-365. <https://doi.org/10.1177/0022219420920377>

- Wang, L.-C., & Yang, H.-M. (2015). Diverse Inhibition and Working Memory of Word Recognition for Dyslexic and Typically Developing Children. *Dyslexia (Chichester, England)*, 21(2), 162-176. <https://doi.org/10.1002/dys.1490>
- Wechsler, D. (2003). *Wechsler Intelligence Scale for Children- Fourth Edition*. . San Antonio, TX: Psychological Corporation.
- Wechsler, D. (2013). *WAIS-IV : Wechsler adult intelligence scale / David Wechsler adattamento italiano a cura di Arturo Orsini e Lina Pezzuti* (4th ed.). Firenze : Giunti O.S.
- Weiss, A. H., Granot, R. Y., & Ahissar, M. (2014). The enigma of dyslexic musicians. *Neuropsychologia*, 54, 28-40. <https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2013.12.009>
- Welbourne, S., Hesketh, A., Woollams, A., & Ainsworth, S. (2018). Contrasting Explicit With Implicit Measures of Children's Representations: The Case of Segmental Phonology. *Language Learning*, 69. <https://doi.org/10.1111/lang.12334>
- Werker, J., & Tees, R. (1987). Speech perception in severely disabled and average reading children. *Canadian journal of psychology*, 41, 48-61. <https://doi.org/10.1037/h0084150>
- Werker, J. F., & Tees, R. C. (2005). Speech perception as a window for understanding plasticity and commitment in language systems of the brain. *Developmental Psychobiology*, 46(3), 233-251. <https://doi.org/10.1002/dev.20060>
- Whelan, R. (2008). Effective Analysis of Reaction Time Data. *The Psychological Record*, 58(3), 475-482. <https://doi.org/10.1007/BF03395630>
- Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., & Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, 4, 1686. <https://doi.org/10.21105/joss.01686>
- Wieling, M. (2018). Analyzing dynamic phonetic data using generalized additive mixed modeling: A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *Journal of Phonetics*, 70. <https://doi.org/10.1016/j.wocn.2018.03.002>
- Wilcockson, T. D. W., Mardanbegi, D., Sawyer, P., Gellersen, H., Xia, B., & Crawford, T. J. (2019). Oculomotor and Inhibitory Control in Dyslexia. *Frontiers in Systems Neuroscience*, 12. <https://doi.org/10.3389/fnsys.2018.00066>
- Willcutt, E. G., Pennington, B. F., Boada, R., Ogline, J. S., Tunick, R. A., Chhabildas, N. A., & Olson, R. K. (2001). A comparison of the cognitive deficits in reading disability and attention-deficit/hyperactivity disorder. *Journal of Abnormal Psychology*, 110(1), 157-172. <https://doi.org/10.1037//0021-843x.110.1.157>
- Williams, G. J., & Wood, C. (2012). Sensitivity to the acoustic correlates of lexical stress and their relationship to reading in skilled readers. *Advances in Cognitive Psychology*, 8(4), 267–280. <https://doi.org/10.2478/v10053-008-0122-0>

- Wilson, A. J., Andrewes, S. G., Struthers, H., Rowe, V. M., Bogdanovic, R., & Waldie, K. E. (2015). Dyscalculia and dyslexia in adults: Cognitive bases of comorbidity. *Learning and Individual Differences*, 37, 118-132. <https://doi.org/https://doi.org/10.1016/j.lindif.2014.11.017>
- Winn, M. B., Edwards, J. R., & Litovsky, R. Y. (2015). The Impact of Auditory Spectral Resolution on Listening Effort Revealed by Pupil Dilation. *Ear Hear*, 36(4), e153-165. <https://doi.org/10.1097/aud.0000000000000145>
- Wolf, M., Gotlieb, R. J. M., Kim, S. A., Pedroza, V., Rhinehart, L. V., Tempini, M. L. G., & Sears, S. (2024). Towards a dynamic, comprehensive conceptualization of dyslexia. *Annals of Dyslexia*, 74(3), 303-324. <https://doi.org/10.1007/s11881-023-00297-1>
- Wood, S. (2011). "Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models." *Journal of the Royal Statistical Society (B)*, 73(1), 3-36.
- Yan, X., Jiang, K., Li, H., Wang, Z., Perkins, K., & Cao, F. (2021). Convergent and divergent brain structural and functional abnormalities associated with developmental dyslexia. *eLife*, 10. <https://doi.org/10.7554/eLife.69523>
- Yoncheva, Y., Maurer, U., Zevin, J. D., & McCandliss, B. D. (2014). Selective attention to phonology dynamically modulates initial encoding of auditory words within the left hemisphere. *NeuroImage*, 97, 262-270. <https://doi.org/10.1016/j.neuroimage.2014.04.006>
- Yoncheva, Y. N., Blau, V. C., Maurer, U., & McCandliss, B. D. (2010). Attentional focus during learning impacts N170 ERP responses to an artificial script. *Developmental neuropsychology*, 35(4), 423-445. <https://doi.org/10.1080/87565641.2010.480918>
- Yu, V., De Nil, L., & Pang, E. (2014, 03/18). Effects of Age, Sex and Syllable Number on Voice Onset Time: Evidence from Children's Voiceless Aspirated Stops. *Language and Speech*, 58. <https://doi.org/10.1177/0023830914522994>
- Zanobini, M., Viterbori, P., & Saraceno, F. (2011). Phonology and Language Development in Italian Children: An Analysis of Production and Accuracy. *Journal of speech, language, and hearing research : JSLHR*, 55, 16-31. [https://doi.org/10.1044/1092-4388\(2011/10-0228\)](https://doi.org/10.1044/1092-4388(2011/10-0228))
- Zarcone, A., van Schijndel, M., Vogels, J., & Demberg, V. (2016). Salience and Attention in Surprisal-Based Accounts of Language Processing. *Frontiers in Psychology*, 7. <https://doi.org/10.3389/fpsyg.2016.00844>
- Zhang, N., & Zhang, Q. (2019). Rhythmic pattern facilitates speech production: An ERP study. *Scientific Reports*, 9(1), 12974-12974. <https://doi.org/10.1038/s41598-019-49375-8>
- Zhao, S., Bury, G., Milne, A., & Chait, M. (2019). Pupillometry as an objective measure of sustained attention in young and older listeners. *Trends in Hearing*, 23, 2331216519887815. <https://doi.org/10.1177/2331216519887815>
- Ziegler, J., & Goswami, U. (2005). Reading Acquisition, Developmental Dyslexia, and Skilled Reading Across Languages: A Psycholinguistic Grain Size Theory. *Psychological bulletin*, 131, 3-29. <https://doi.org/10.1037/0033-2909.131.1.3>

- Ziegler, J. C., Bertrand, D., Tóth, D., Csépe, V., Reis, A., Faisca, L., Saine, N., Lyytinen, H., Vaessen, A., & Blomert, L. (2010). Orthographic depth and its impact on universal predictors of reading: A cross-language investigation. *Psychological Science, 21*(4), 551–559. <https://doi.org/10.1177/0956797610363406>
- Ziegler, J. C., Perry, C., Ma-Wyatt, A., Ladner, D., & Schulte-Körne, G. (2003). Developmental dyslexia in different languages: Language-specific or universal? *Journal of experimental child psychology, 86*(3), 169-193. [https://doi.org/https://doi.org/10.1016/S0022-0965\(03\)00139-5](https://doi.org/https://doi.org/10.1016/S0022-0965(03)00139-5)
- Ziegler, J. C., Perry, C., & Zorzi, M. (2020). Learning to Read and Dyslexia: From Theory to Intervention Through Personalized Computational Models. *Current directions in psychological science, 29*(3), 293-300. <https://doi.org/10.1177/0963721420915873>
- Zoubinetzky, R., Collet, G., Serniclaes, W., Nguyen-Morel, M. A., & Valdois, S. (2016). Relationships between Categorical Perception of Phonemes, Phoneme Awareness, and Visual Attention Span in Developmental Dyslexia. *PLoS One, 11*(3), e0151015. <https://doi.org/10.1371/journal.pone.0151015>
- Zuk, J., Perdue, M. V., Becker, B., Yu, X., Chang, M., Raschle, N. M., & Gaab, N. (2018). Neural correlates of phonological processing: Disrupted in children with dyslexia and enhanced in musically trained children. *Developmental Cognitive Neuroscience, 34*, 82-91. <https://doi.org/https://doi.org/10.1016/j.dcn.2018.07.001>

## 7. Appendices

### 7.1 Appendix A

#### Adolescents Phoneme Monitoring Stimuli embedding Targets: /p/ and /m/

##### Target /p/

Singleton	Geminate
[skaFO <b>ni</b> po <b>re</b> ]	[karDO <b>ni</b> ppo <b>ze</b> ]
[zaKA <b>ra</b> pu <b>ba</b> ]	[graGA <b>na</b> ppu <b>ba</b> ]
[sfu <b>pe</b> tʃiGA <b>ne</b> ]	[vu <b>pp</b> eddʒiKA <b>de</b> ]
[bi <b>po</b> zaVI <b>ba</b> ]	[bri <b>pp</b> onaFI <b>ba</b> ]
[skofena <b>PO</b> ri]	[kordena <b>PP</b> Ori]
[zekori <b>PU</b> bo]	[gregoni <b>PP</b> Ubo]
[sfo <b>PE</b> tʃiguna]	[vo <b>PP</b> edʒikuda]
[be <b>PO</b> zuvibe]	[bre <b>PP</b> Ozufibe]

##### Target /m/

[zgaVO <b>bi</b> more]	[garDO <b>si</b> mmoddze]
[saGA <b>ra</b> muna]	[kraTS <b>Ad</b> ammuna]
[zvum <b>ed</b> dʒiTS <b>A</b> ne]	[fum <b>me</b> tʃiKA <b>R</b> de]
[ni <b>mo</b> zaVI <b>na</b> ]	[ni <b>mm</b> ozarFI <b>na</b> ]
[zgovabu <b>MA</b> ro]	[gordasu <b>MM</b> Addzo]
[segora <b>MI</b> nu]	[kretsoda <b>MM</b> Inu]
[no <b>MO</b> zevane]	[fo <b>MM</b> Atʃikordi]
[zvo <b>MA</b> dʒitsoni]	[no <b>MM</b> Ozerfane]

*Note.* To enhance readability, capital letters indicate target phonemes, and bold font indicates the syllable carrying lexical stress.

## 7.2 Appendix B

### Sentence Stimuli for the SMS Task (Adolescent Group)

<b>Italian sentence</b>	<b>English translation</b>
Le ragazze cercano le collane.	The girls look for the necklaces.
Le sorelle raggiungono le amiche.	The sisters reach their friends.
Le sculture ritraggono le api.	The sculptures portray the bees.
Le voci rispettano le attrici.	The voices respect the actresses.
Le clavi le lanciano le ginnaste.	The clubs are thrown by the gymnasts.
Le storie le donne le raccontano con pazienza.	The stories are told patiently by the women.
Avendo richiesto solo le frittelle, ce le cucini oggi a merenda?	Having asked only for pancakes, will you cook them for me today at snack time?
Gli gnomi mangiano gli zuccherini.	The gnomes eat the little sugared sweets.
Gli stambecchi raggiungono gli alpeggi.	The ibexes reach the alpine pastures.
Gli scoppi segnalano gli arrivi.	The explosions signal the arrivals.
Gli scambi li rischiano gli azzurri.	The exchanges are risked by the blue team.
Gli zaini li indossa l'attore.	The backpacks are worn by the actor.
Gli specchi gli attrezzisti li portano da soli.	The stagehands carry the mirrors by themselves.
Da domani, gli occhiali me li ancori alla corda per non perderli?	Starting tomorrow, will you fasten my glasses to the cord so I don't lose them?
Lo psicologo raggiunge lo studio.	The psychologist reaches the office.
Lo sparo annuncia l'inizio.	The shot announces the beginning.
Lo stagno riflette lo psichiatra.	The pond reflects the psychiatrist.
Lo zuccotto lo compra lo spazzino.	The sponge cake is bought by the garbage collector.
Lo spazzolino lo darà lo zio.	The toothbrush will be given by the uncle.
Lo strutto lo scrittore lo regala a Pasqua.	The lard is given as a present by the writer at Easter.
Avendo richiesto solo lo spezzatino, ce lo cucinerà oggi per cena?	Having asked only for the stew, will he cook it for us today for dinner?

### 7.3 Appendix C

#### Children Phoneme Monitoring Stimuli Embedding Targets: /t/ and /l/

Target /t/	
Singleton	Geminate
[se <b>T</b> Aodeluvi]	[re <b>TT</b> Epozenufe]
[re <b>T</b> Asofeduri]	[me <b>TT</b> Asofeduri]
[suvena <b>L</b> Atelumi]	[rofida <b>R</b> Attelufi]
[fuzane <b>R</b> Atemuli]	[mideka <b>R</b> Attemidi]
[maka <b>R</b> Alutani]	[fekoma <b>D</b> Aluttana]
[nogo <b>L</b> Arutame]	[muso <b>L</b> Aruttadi]
[fema <b>P</b> Osomituri]	[gose <b>K</b> Oromittudo]
[finu <b>K</b> Osunituzi]	[jesu <b>K</b> Orenittudi]
Target /l/	
[garadapi <b>L</b> Ufe]	[tamorasi <b>LL</b> Uvo]
[davamadi <b>L</b> Ure]	[seranami <b>LL</b> Uke]
[faʃina <b>T</b> Elekuni]	[veʃenu <b>T</b> Ellerumi]
[kaʃeva <b>T</b> Eleguni]	[gaʃiva <b>T</b> Ellegome]
[sepu <b>M</b> Arulasi]	[reku <b>M</b> Adullane]
[febu <b>M</b> Iruladi]	[bufo <b>M</b> Isullako]
[ro <b>Z</b> Akadalufane]	[su <b>R</b> Agodallufesi]
[re <b>Z</b> Agadalugani]	[si <b>G</b> Asadallugone]

*Note.* To enhance readability, capital letters indicate target phonemes, and bold font indicates the syllable carrying lexical stress.