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Neurophysiologische Korrelate der Worterkennung bei Kindern mit isolierter Lese- und/oder Rechtschreibstörung

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INHALTSVERZEICHNIS

ZUSAMMENFASSUNG

Während die kognitiven und neurophysiologischen Grundlagen von Lese-Rechtschreibstörungen (LRS) schon relativ gut erforscht sind, sind Studien welche Lese- und Rechtschreibprobleme unabhängig voneinander untersuchen, immer noch sehr selten. Dabei zeigen neuere Prävalenzstudien, dass Probleme im Lesen und Probleme im Rechtschreiben dissoziieren können und isolierte Störungen in etwa genauso häufig auftreten wie kombinierte Lese-Rechtschreibstörungen. Demnach haben ca. 7% der Kinder eine isolierte Rechtschreibstörung, 6-7% eine isolierte Lesestörung und 7-8% eine kombinierte Lese- und Rechtschreibstörung (Moll et al., 2014; Moll & Landerl, 2009).

Trotz dieser hohen Prävalenzrate der isolierten Störungen gibt es bis heute noch keine ausreichende Information über die Ursachen und neurobiologischen Korrelate dieser Störungen. Kognitive Verhaltenstestungen weisen darauf hin, dass langsames Lesen mit Problemen im schnellen Benennen von in Reihen dargebotenen Stimuli (Buchstaben, Ziffern, Objekte oder Farben) zusammenhängt, während Probleme im Rechtschreiben mit schwacher phonologischer und orthografischer Verarbeitung einhergehen (Moll & Landerl, 2009). Diese mit dem Lesen bzw. Rechtschreiben assoziierten kognitiven Defizite lassen vermuten, dass bei Lesestörungen der Zugriff von einem visuellen Symbol auf die entsprechende Phonologie verzögert sein könnte. Im Gegensatz dazu wäre der Zugriff im Falle einer isolierten Rechtschreibstörung zwar schnell genug, die orthografischen Inhalte aber ungenau oder fehlend (Frith, 1985).

Die vorliegende Dissertation hatte das Ziel, diese Annahmen mittels neurophysiologischer Methoden zu überprüfen. Dazu wurden in vier Gruppen von Kindern Elektroenzephalogramme (EEG) im Rahmen von zwei unterschiedlichen Experimenten abgeleitet: Kinder mit einer isolierten Lesestörung aber altersgemäßer Rechtschreibleistung (iLS), Kinder mit einer isolierten Rechtschreibstörung und altersgemäßer Leseleistung (iRS) und Kinder mit einer kombinierten Lese-Rechtschreibstörung (LRS) wurden im Vergleich zu typisch entwickelten (TE) Kindern untersucht. Die hohe zeitliche Auflösung der EEG-Messung ermöglicht es, den relativ schnellen Prozess des phonologischen und orthografischen Zugriffs in Echtzeit zu erfassen, um so die vermutete Zugriffsverzögerung zu überprüfen.

In Experiment/Studie 1 wurde mithilfe einer phonologisch-lexikalischen Entscheidungsaufgabe die orthografische Verarbeitung untersucht. Die Kinder sahen Wörter (z.B.: Mund), Pseudohomophone (gleiche Aussprache, aber falsche Schreibweise z.B.: Munt) und Pseudowörter (z.B.: Mukk) und mussten per Tastendruck entscheiden, ob diese so klangen wie ein richtiges Wort. Kinder mit iLS zeigten ähnliche neurophysiologische Muster

wie TE Kinder: Die LPC (late positive complex), ein mit dem orthografischen Abruf assoziiertes EKP (ereigniskorrelierte Potential), war für Wörter, im Vergleich zu Pseudohomophonen erhöht. Die Wortverarbeitung dauerte in der iLS Gruppe allerdings länger, was auf einen langsamen Zugriff hinweist. In der iRS und LRS Gruppe gab es keine Erhöhung der LPC auf Wörter im Vergleich zu Pseudohomophonen, was darauf schließen lässt, dass Kinder mit Rechtschreibstörungen weniger orthografische Repräsentationen (Gedächtniseintrag, wie ein Wort geschrieben wird) zur Verfügung haben.

In Experiment/Studie 2 haben wir phonologische Prozesse in einem neu entwickelten EEG-Paradigma untersucht. Die Aufgabe der Kinder bestand darin, zwei visuell präsentierte Buchstaben miteinander zu vergleichen. In der inkongruenten Bedingung (z. B.: A a) waren die phonologischen Eigenschaften der Buchstaben gleich (beide repräsentieren den gleichen Laut), bei ungleichen visuellen Merkmalen. In der kongruenten Bedingung waren sowohl die phonologischen als auch die visuellen Merkmale der Buchstaben ungleich (z. B.: A e). Wenn Buchstabe-Laut-Verbindungen stark und hoch automatisiert sind, sollte das in einem kognitiven Konflikt in der inkongruenten Bedingung resultieren, da in dem Fall nicht nur die visuellen, sondern auch die phonologischen Informationen automatisch abgerufen werden. Dieser Konflikt konnte in den EKPs N1, N2 und cSP (conflict slow potential) abgebildet werden. Wir haben TE Kinder und Kinder mit einer LRS untersucht und eine verminderte Automatisierung in der LRS Gruppe festgestellt. Der kognitive Konflikt resultierte in einer verminderten N1 und einer erhöhten cSP Amplitude in der TE Gruppe, aber nicht in der LRS Gruppe. Die Auswertung der isolierten Lese- und Rechtschreibstörungsgruppen ist hierbei noch ausstehend.

SUMMARY

Although the cognitive and neurophysiological correlates of reading-spelling disorders (RSD) are already well understood, studies analyzing deficits in reading and spelling individually are still very rare. Recent prevalence studies have shown that isolated disorders are nearly as common as combined reading-spelling disorders, thus there are some dissociations between reading and spelling skills. Approximately 7% of children have an isolated spelling disorder, 6-7% an isolated reading disorder and 7-8% a combined reading-spelling disorder (Moll et al., 2014; Moll & Landerl, 2009).

Surprisingly, even though prevalence rates of isolated disorders are high, there is a lack of information about the neurobiological correlates of these disorders. Cognitive-behavioral studies imply that slow reading might be related to difficulties in rapid naming of serially presented items (letters, digits, objects or colors), whereas spelling problems rather relate to weak phonological and orthographic processing (Moll & Landerl, 2009). Thus, deficits associated separately with reading versus spelling problems imply that in reading disorders the access from visual stimuli to the respective phonology might be delayed. In contrast, in isolated spelling disorders, the access might be fast enough by missing or vaguely defined orthographic representations (Frith, 1985). The present work had the goal to examine these assumptions by means of neurophysiological measurements. For this purpose, we conducted two different experiments in four groups of children using electroencephalogram (EEG): We examined a group of children with isolated reading disorder (iRD) but age-appropriate spelling skills, a group of children with isolated spelling disorder (iSD) and age-adequate reading skills and a group of children with a combined reading-spelling disorder (RSD) and compared these groups to a group of typically developing (TD) children. The high temporal resolution of the EEG measurement was important to collect data about the relatively fast process of phonological and orthographic access, and thus examine the hypothesis of a delayed processing.

In experiment/study 1, orthographic processes have been examined within the framework of a phonological-lexical decision task. The children saw words (e.g. rain), pseudohomophones (e.g. rane) and pseudowords (e.g. hasz) and had to decide via button-press whether these stimuli sounded like real words. Children with iRD showed similar neurophysiological patterns like TD children: the LPC (late positive complex), an ERP (event-related potential) component associated with access to the orthographic lexicon was higher to words than to pseudohomophones. However, word processing took longer in the iRD group, which might imply a delayed access. In the iSD and RSD groups, the LPC was comparable between words

and pseudohomophones, thus, fewer orthographic representations (memory trace about the spelling of a word) might be available for children with spelling disorders compared to TD children.

In experiment/study 2, we examined phonological processes in a newly developed EEG-paradigm. The task of the children was to compare two visually presented letters. In the incongruent condition (e.g. A a), the two presented letters shared the same phonology (as they represented the same sound), but differed in their visual characteristics. In the congruent condition (e.g. A e), the presented letters did differ in both their phonological and visual characteristics. If letter-speech sound-associations are highly automatized, a cognitive conflict should occur in the incongruent condition, because two types of information compete: the visual and the automatically accessed phonological information. This cognitive conflict has been captured in the ERPs N1, N2 and cSP (conflict slow potential). We compared TD children and children with RSD and found less automatized letter-speech sound-associations in the RSD group. Thus, cognitive conflict resulted in a reduced N1 and enlarged cSP in the TD group, but not in the RSD group. The analysis of the iRD and iSD groups is still ongoing.

EINLEITUNG ZUR KUMULATIVEN DISSERTATION

HINTERGRUND

Lese- und Rechtschreibstörungen (auch Dyslexie oder Legasthenie genannt) sind Entwicklungsstörungen schulischer Fertigkeiten, die durch eine deutlich verlangsamte Lesegeschwindigkeit und/oder eine beeinträchtigte Lesegenauigkeit, beziehungsweise durch erhebliche Schwierigkeiten beim orthografischen Schreiben gekennzeichnet sind. Diese Schwierigkeiten entstehen trotz durchschnittlicher Intelligenz, uneingeschränkter Hör- und Sehfähigkeiten und regulärer Beschulung (Schulte-Körne, 2011). Das Internationale Klassifikationssystem psychischer Störungen (ICD-10) unterscheidet dabei zwischen einer Lese- und Rechtschreibstörung (F81.0) und einer isolierten Rechtschreibstörung (F81.1) (Dilling, Mombour, & Schmidt, 2008). Die isolierte Lesestörung (iLS) wird bis jetzt nicht als eine eigene Diagnosekategorie geführt, obwohl Prävalenzstudien darauf hinweisen, dass in konsistenten Orthographien, wie es die deutsche Orthographie ist, isolierte Störungen der Leseflüssigkeit fast genauso häufig auftreten wie kombinierte Lese-Rechtschreibstörungen. Abhängig von den Diagnosekriterien beträgt die Prävalenzrate der isolierten Rechtschreibstörung (iRS) 7%, der isolierten Lesestörung (iLS) 6-7% und der kombinierten Lese-Rechtschreibstörung (LRS) 7-8% (Moll et al., 2014, Moll & Landerl, 2009). Lese- und/oder Rechtschreibstörungen gehören dementsprechend zu den häufigsten umschriebenen Entwicklungsstörungen.

Schwierigkeiten im Schriftspracherwerb haben negative Auswirkungen nicht nur auf den schulischen und akademischen Werdegang, sondern beeinflussen den späteren beruflichen Erfolg und die psychische Gesundheit der Betroffenen (Schulte-Körne et al., 2003). Ungefähr bei 40% der Kinder, bei denen eine Lese- und/oder Rechtschreibstörung diagnostiziert wurde, wird im Laufe der Zeit eine weitere komorbide psychische Störung diagnostiziert, wie zum Beispiel eine Depression, Aufmerksamkeitsdefizit-Hyperaktivitätsstörung (ADHS) oder eine Angststörung (Schulte-Körne, 2010).

Wegen der relativ großen Häufigkeit und der Schwere der möglichen Folgen für den Betroffenen ist es sehr wichtig, die Ätiologie und Pathogenese dieser Störungen so genau wie möglich zu verstehen. Nach aktuellem Stand der Forschung spielen dabei neben Umweltfaktoren auch genetische und neurobiologische Faktoren eine große Rolle (Caylak, 2009; Richlan, 2012; Richlan, Kronbichler, & Wimmer, 2011; Shaywitz & Shaywitz, 2008; Xia, Hancock, & Hoeft, 2017). Kognitive Neurowissenschaften könnten also einen wichtigen

Beitrag leisten, die Entstehung der Störung besser zu verstehen. Dadurch könnten frühe Identifikation und schnellstmögliche Intervention verbessert werden.

Bis zum heutigen Zeitpunkt haben sich neurophysiologische Studien allerdings vorwiegend auf die Untersuchung von LRS und gelegentlich auf iRS fokussiert. Die Erforschung von isolierten Lesestörungen steht noch am Anfang. Da isolierte und kombinierte Störungen des Lese- und Rechtschreiberwerbs unterschiedliche kognitive Profile aufweisen (Moll & Landerl, 2009; Wimmer & Mayringer, 2002), kann die vorhandene Literatur zur LRS keine eindeutigen Rückschlüsse über die neurobiologische Entwicklung der Kinder mit einer iLS liefern. Untersuchungen zu neurophysiologischen Grundlagen der iLS sind also dringend notwendig.

Mögliche Ursachen von isolierten Lese- und isolierten Rechtschreibstörungen

Kinder mit einer isolierten Lesestörung zeigen eine deutlich verlangsamte Lesegeschwindigkeit bei einer altersgemäßen Rechtschreibleistung. Im Gegensatz dazu weisen Kinder mit einer isolierten Rechtschreibstörung eine unterdurchschnittliche Rechtschreibleistung auf, zeigen aber keine Beeinträchtigungen der Leseflüssigkeit (Moll & Landerl, 2009; Schulte-Körne, 2011; Wimmer & Mayringer, 2002).

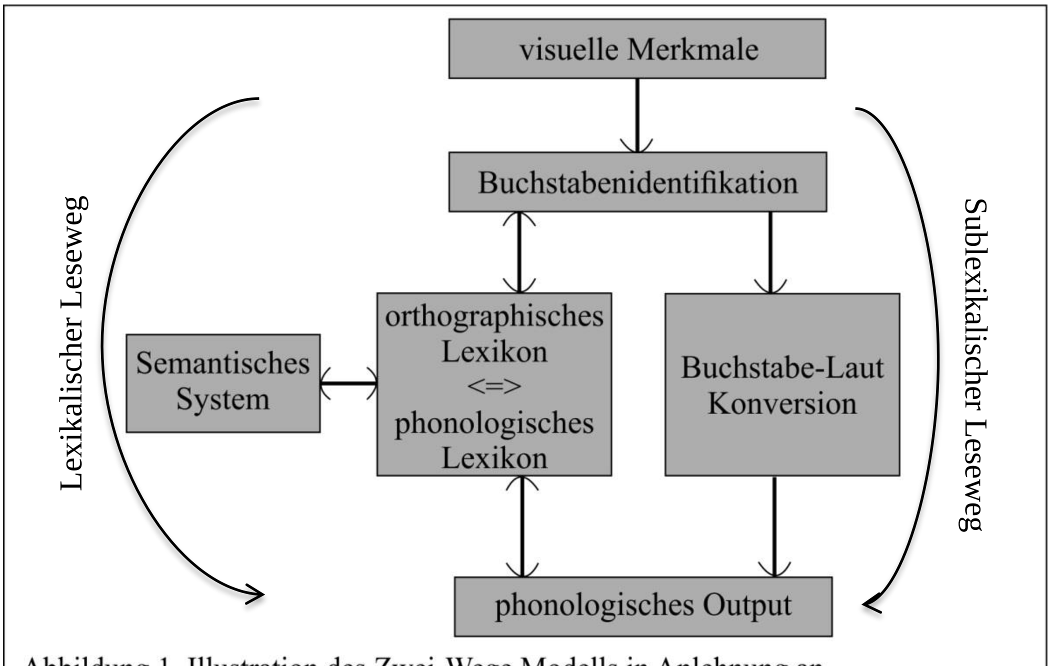

Abbildung 1. Illustration des Zwei-Wege Modells in Anlehnung an Schulte-Körne (2011).

Wimmer und Mayringer (2002) nahmen an, dass das langsame Lesen bei iLS durch eine Verlangsamung des phonologischen Zugriffes verursacht wird, während eine iRS durch das Fehlen von orthografischen Wortrepräsentationen erklärt werden kann. Diese Annahmen basieren auf dem Zwei-Wege-Modell des Lesens (Bergmann & Wimmer, 2008; Coltheart et al., 1993; Coltheart et al., 2001). Das Zwei-Wege-Modell des Lesens geht von zwei möglichen Prozessen beim Lesen aus: (1) Beim Lesen von bekannten Wörtern wird von der visuellen Form des Wortes (Buchstabenfolge) ausgehend auf eine eingespeicherte Repräsentation im orthografischen Lexikon zugegriffen, was direkt zum phonologischen Output führt. Dieser Weg wird auch lexikalisches Lesen genannt. (2) Beim Lesen von unbekannten Wörtern wird der phonologische Output durch das Zusammenlauten der einzelnen buchstabenassoziierten Laute generiert. Das Wort wird also buchstabenweise oder zumindest in kleinen sublexikalischen Einheiten durch Zusammenlauten „erlesen". Dies nennt man auch sublexikalisches Lesen (siehe auch Abbildung 1).

Da die Rechtschreibleistung der Kinder mit einer iLS unbeeinträchtigt ist, wurde von Wimmer und Mayringer (2002) angenommen, dass Kinder mit einer iLS über intakte orthografische Wortrepräsentationen verfügen. Orthografische Repräsentationen sind für das Rechtschreiben essentiell, da die orthografisch korrekte Schreibweise eines Wortes nur in seltenen Fällen hundertprozentig mit den gehörten Lauten übereinstimmt. Das gehörte Wort /ˊfa:tɐ/ könnte man zum Beispiel sowohl mit „F", als auch mit „V" verschriftlichen. Also nur dann, wenn der orthografische Gedächtniseintrag „Vater" vorhanden ist, kann man das Wort richtig schreiben. Diese orthografischen Repräsentationen dienen aber nicht nur zum Schreiben, sondern können auch die Leseflüssigkeit erhöhen. Sobald intakte Repräsentationen vorhanden sind, muss man ein Wort nicht mehr dekodierend (buchstabenweise) erlesen, sondern man kann den schnelleren, lexikalischen Weg gehen und das Wort als gespeicherte Einheit aus dem Lexikon abrufen. Warum lesen also Kinder mit iLS langsam, wenn sie über intakte orthografische Repräsentationen verfügen? Die Erklärung dafür wäre, dass nicht die orthografische Repräsentation selbst, sondern der Zugriff darauf beeinträchtigt ist. Langsames Zugreifen auf vorhandene Repräsentationen ist unproblematisch für den relativ langsamen Prozess des Schreibens, verlangsamt aber womöglich den Leseprozess.

Im Gegensatz dazu wird vermutet, dass Kinder mit einer isolierten Rechtschreibstörung Probleme im Aufbau des wortspezifischen orthografischen Lexikons haben, was die schwache Rechtschreibleistung der Betroffenen erklärt. Für das altersentsprechende Lesen in dieser Gruppe lassen sich zwei Erklärungsansätze unterscheiden: Erstens, orthografische Repräsentationen könnten unvollständig und ungenau definiert sein (Frith, 1985), was für das

Wiedererkennen (sprich Lesen) eines Wortes noch ausreichend wäre, aber nicht für die selbstständige Produktion (sprich Schreiben). Zweitens, Kinder mit iRS könnten das Fehlen von orthografischen Repräsentationen mit höchst effizientem dekodierendem Lesen (sublexikalisches Buchstabe-zu-Buchstabe Lesen) kompensieren. Letzteres wäre allerdings nur in einer relativ konsistenten Orthografie wie dem deutschen möglich, in dem es wenig irreguläre Wörter gibt und somit das Zusammenlauten der einzelnen Buchstaben zur richtigen Aussprache führt.

Zusammengefasst kann festgestellt werden, dass bei der Untersuchung von Lese- und/oder Rechtschreibstörungen sowohl lexikalische als auch sublexikalische Prozesse als mögliche Problembereiche untersucht werden müssen. Außerdem ist es wichtig, den zeitlichen Ablauf des orthographischen und phonologischen Abrufes genau zu erfassen, um so zwischen einer Zugriffsproblematik und einer Problematik im Aufbau von orthografischen Repräsentationen unterscheiden zu können.

Neurophysiologische Korrelate des Leseprozesses

Die neurobiologische Forschung hat schon große Fortschritte in der Identifikation der am Lesen beteiligten Gehirnstrukturen und neurophysiologischen Prozesse erreicht. Es wurde gezeigt, dass beim Lesen ein linkshemisphärisches Netzwerk, bestehend aus kortikalen und subkortikalen Hirnarealen aktiviert wird (auch als neuronales Lesenetzwerk bezeichnet – Shaywitz et al., 2002; Shaywitz, Gruen, & Shaywitz, 2007; Shaywitz & Shaywitz, 2008). Dem lexikalen Leseweg wurde eine ventrale Route, unter anderem mit Beteiligung des visuellen Wortformareals (VWFA) zugeordnet. Das VWFA liegt ventral zwischen okzipitalen und temporalen Gehirnarealen und ist an der schnellen, automatischen Identifizierung von Wörtern oder Buchstaben beteiligt. Auf diesem Wege werden bekannte, im orthografischen Lexikon abgespeicherte Wörter gelesen (Kronbichler et al., 2007; Kronbichler et al., 2004; Wimmer et al., 2010). Bei unbekannten Wörtern wird der phonologische Output anhand von Graphem-Phonem (Buchstabe-Laut) Zuordnungen generiert, also auf dem sublexikalischen Weg. Diesem Weg wurde eine dorsale Route mit Einbeziehung parieto-temporaler Gehirnareale zugeordnet. Allerdings ist bei der Erkennung von Buchstaben das VWFA ebenfalls beteiligt (Blau et al., 2010; Sandak et al., 2004). Der letzte Schritt des Leseprozesses, der Abruf von sowohl lexikalischen als auch sublexikalischen phonologischen Repräsentationen und die Vorbereitung der Artikulation passiert in inferior frontalen Gehirnregionen, die in beiden Lesewegen involviert sind (Richlan, 2012; Shaywitz & Shaywitz, 2008).

Auch der zeitliche Ablauf der *lexikalischen* Worterkennung wurde bereits in Experimenten mit Elektroenzephalografie (EEG) untersucht. Mithilfe eines Wortleseexperimentes verbunden mit einer phonologisch-lexikalischen Entscheidungsaufgabe konnten Hasko et al. (2013) zum Beispiel einzelne Zeitfenster (ereigniskorrelierte Potentiale; EKP) identifizieren und dem lexikalen Prozess zuordnen. Die N170, gemessen über dem okzipito-temporalen Kortex bis ca. 200 ms nach der Präsentation eines Wortes, spiegelt die erste Stufe der Wortverarbeitung, die visuell-orthographische Verarbeitung, wider (Hasko et al., 2013). Bei geübten Lesern wurden höhere N170 Amplituden beim Anschauen von orthografischen Stimuli (z.B.: Buchstabenfolgen) im Vergleich zu nicht-orthografischen Stimuli (z.B.: graphische Zeichenfolgen) gefunden (Bentin et al., 1999; Maurer, Brandeis, & McCandliss, 2005). Die N400, gemessen über zentro-parietalen Bereichen um ca. 400 ms, wurde am häufigsten mit semantischen Prozessen assoziiert (Kutas & Federmeier, 2011; Münte et al., 2000). Die LPC (late positive complex), gemessen über links-lateralen parietalen Bereichen ca. 500 ms nach der Präsentation eines Wortes, wurde mit lexikalischen Prozessen, wie zum Beispiel dem Zugriff auf das orthografische Lexikon, in Zusammenhang gebracht (Balass, Nelson, & Perfetti, 2010; Rugg & Curran, 2007). Dieses EKP ist erhöht für eingespeicherte (gelernte) Wörter im Vergleich zu neuen Wörtern (Schulte-Körne et al., 2004).

Die Neurophysiologie *sublexikalischer* Prozesse wurde mittels unbekannter Wörter (Pseudowörter) erforscht. Für die Lesegeschwindigkeit von unbekannten Wörtern ist der Grad der Automatisierung von Buchstabe-Laut Beziehungen maßgeblich entscheidend, da diese Wörter buchstabenweise oder in kleinen Einheiten auf dem sublexikalischen Leseweg „erlesen" werden. In passiven Oddball-Experimenten mit parallel präsentierten Buchstaben- und Lauten als Stimuli (visuell-auditives Oddball) wurde eine verminderte Linkslateralisierung in fronto-zentalen (100-190 ms) und parieto-temporalen Bereichen (560-750 ms) mit Lese-Rechtschreibstörung assoziiert (Moll et al., 2016).

ÜBERSICHT ZU DEN PUBLIZIERTEN FACHARTIKELN, die die Grundlage der kumulativen Dissertation sind.

Übergeordnetes Ziel und Ergebniszusammenfassung

Vor diesem Hintergrund hatte die vorliegende Dissertation das Ziel, neurophysiologische Korrelate der Worterkennung sowohl auf der lexikalischen als auch auf der sublexikalischen Ebene bei Kindern mit isolierter Lese- und/oder Rechtschreibstörung zu untersuchen. Um dieses Ziel zu erreichen, wurden bei vier Gruppen von Kindern (Kinder mit iLS, Kinder mit iRS, Kinder mit LRS und Kinder ohne Lese- und Rechtschreibprobleme) in zwei unterschiedlichen Experimenten Elektroenzephalogramme (EEG) abgeleitet. Die hohe zeitliche Auflösung des EEGs erlaubt die Messung neurophysiologischer Prozesse in Echtzeit, wodurch einzelne Verarbeitungsschritte im Leseprozess erfasst und Unterschiede zwischen den Gruppen aufgedeckt werden können. Dies ist besonders wichtig, um eventuelle Zugriffsverzögerungen in der iLS Gruppe feststellen zu können.

Ziel von Studie 1 war es, lexikalische und soweit möglich sublexikalische Prozesse während der Worterkennung zu untersuchen, um so mögliche Unterschiede zwischen typisch entwickelten (TE) Kindern und Kindern mit iLS, iRS und LRS zu entdecken. Dazu wurde

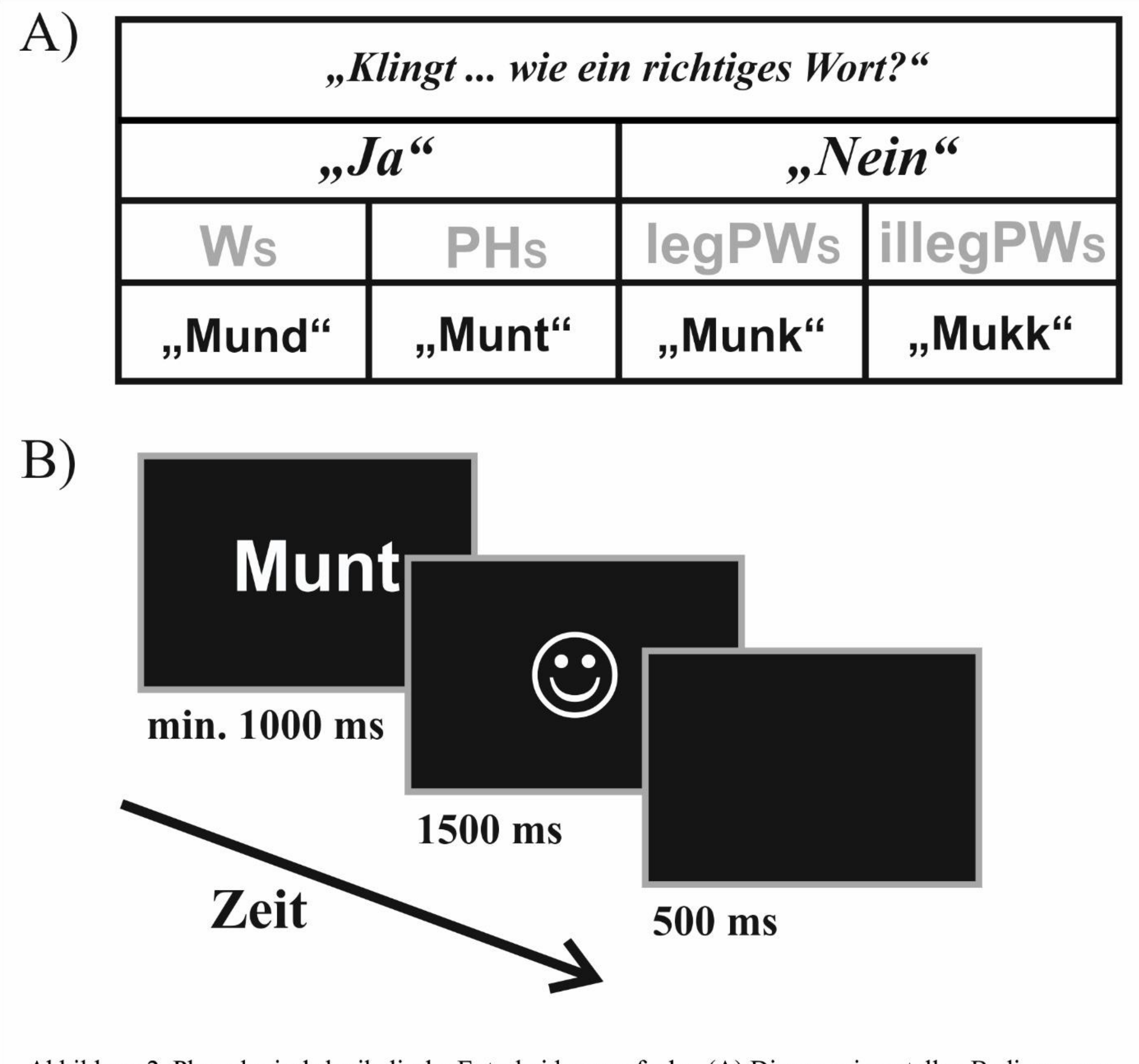

Abbildung 2. Phonologisch-lexikalische Entscheidungsaufgabe. (A) Die experimentellen Bedingungen mit jeweils einer Beispielitem. (B) Exemplarische Darstellung eines Trials. Die Teilnehmer wurden gebeten, per Tastendruck zu entscheiden, ob das präsentierte Item so klingt wie ein richtiges Wort oder nicht, und erhielten nach der Entscheidung sofort ein Feedback.

eine phonologisch-lexikalische Entscheidungsaufgabe (siehe Abbildung 2) während der EEG-Messung durchgeführt und die Ergebnisse in vier Gruppen mit neunjährigen Kindern analysiert: In einer Gruppe von Kindern mit iLS (n=21), einer Gruppe von Kindern mit iRS (n=21), einer Gruppe von Kindern mit LRS (n=33) und einer Gruppe typisch entwickelter (TE) Kinder (n=36), welche als Kontrollgruppe diente. Den Kindern wurden Wörter (W – z.B.: Mund), Pseudohomophone (PH – z.B.: Munt), legale Pseudowörter (legPW – z.B.: Munk) und illegale Pseudowörter (illegPW – z.B.: Mukk) präsentiert. IllegPW enthielten Buchstabenfolgen, welche im Deutschen nicht existieren. Die Aufgabe bestand darin, zu entscheiden, ob die präsentierte Buchstabenfolge klingt wie ein richtiges Wort oder nicht (siehe Abbildung 2). Die untersuchten EKPs, d.h. die N170, die N400 und die LPC wurden in zwei getrennten Analysen ausgewertet: (1) Der Vergleich zwischen W und PH (Mund vs. Munt) sollte über lexikalisch-orthografische Prozesse Aufschluss geben, da die Aussprache (Phonologie) der beiden Bedingungen gleich ist, so dass die Bedingungen sich nur in der Orthografie bzw. im Vorhandensein eines orthografischen Eintrages im Lexikon unterschieden. (2) Der Vergleich legPW versus illegPW (Munk vs. Mukk) gibt Aufschluss über die sublexikalische Sensitivität für erlaubte orthografische Muster der deutschen Sprache. IllegPW enthielten im Kontrast zu legPW unerlaubte Buchstabenfolgen, welche die deutsche Orthografie verletzen.

Verglichen mit der Kontrollgruppe zeigten alle Defizitgruppen in der frühen Komponente N170 eine generell verminderte Sensitivität für orthografisches Material. Erstens war die N170 Amplitudenhöhe zu W und PH kleiner bei Kindern mit iLS, iRS und LRS als bei TE Kindern. Zweitens zeigten nur TE Kinder eine unterschiedliche Ausprägung der N170 in Abhängigkeit von der Gültigkeit des orthografischen Musters (legPW vs. illegPW). TE Kinder zeigten höhere N170 Amplituden bei illegPW im Vergleich zu legPW in der rechten Hemisphäre, was auf eine Einordnung der illegPW als „nicht-orthografisches" Material hindeuten könnte (für die Auflistung der Ergebnisse siehe Tabelle 1). Dies ist im Einklang mit der Literatur; das Betrachten von nicht-orthografischem Material (z.B.: visuelle Zeichen) erzeugte höhere N170 in der rechten Hemisphäre als das Betrachten von orthografischem Material (z.B.: Buchstaben), während in der linken Hemisphäre das Umgekehrte Muster beobachtet wurde (Bentin et al., 1999; Maurer & McCandliss, 2008).

Des Weiteren konnten Unterschiede zwischen den Gruppen in der LPC festgestellt werden. Diese Komponente spiegelt den orthografisch-lexikalischen Abruf wider, weil sie üblicherweise bei Wörtern im Gegensatz zu Nicht-Wörtern erhöht ist. TE Kinder und Kinder mit iLS zeigten eine stabile LPC-Erhöhung für Wörter, was darauf schließen lässt, dass beide

Tabelle 1. Auflistung der Ergebnisse von Studie 1.

<table>
<tr><td colspan="4">Komponente im W-PH-Vergleich (lexikalisch-orthografische Prozesse)</td></tr>
<tr><td>N170
(visuell-orth. Verarbeitung)</td><td colspan="3">TE-Kinder > iLS = iRS = LRS</td></tr>
<tr><td>N400
(semantische Verarbeitung)</td><td colspan="3">Keine Unterschiede</td></tr>
<tr><td>LPC
(Zugriff auf orth.
Repräsentationen</td><td>TE: W>PH</td><td>iLS: W > PH, aber langsamer als TE</td><td>iRS und LRS: W = PH
Itemanalyse nur Korrekt geschriebene Wörter: W > PH</td></tr>
<tr><td colspan="4">Komponente im legPW-illegPW-Vergleich (sublexikalischer Sensitivität)</td></tr>
<tr><td>N170
(visuell-orth. Familiarität)</td><td colspan="2">TE:
legPW: stärkere linkshemispherische Verarbeitung
illegPW: stärkere rechtshemispherische Verarbeitung</td><td>iLS, iRS und LRS:
keine Unterschiede</td></tr>
<tr><td>N400
(semantische Verarbeitung)</td><td colspan="3">Keine Unterschiede</td></tr>
</table>

Gruppen über orthografische Repräsentationen verfügen. Die LPC Komponente in der Gruppe mit iLS dauerte allerdings länger an als in der TE Gruppe, was auf eine verlangsamte Verarbeitung oder einen verlangsamten Abruf schließen lässt (siehe Tabelle 1).

In der LRS und iRS Gruppe konnten wir zunächst keine stabile LPC-Erhöhung feststellen. Da zusätzlich zur EEG-Messung das Rechtschreibwissen der Kinder zu den experimentellen Wörtern erhoben wurde, war es uns möglich, item-basierte Analysen durchführen. Hierfür haben wir die neurophysiologischen Muster in den beiden Rechtschreibstörungsgruppen (LRS und iRS) getrennt für richtig und falsch geschriebene Wörter analysiert. Dies war möglich, weil unser verwendetes Wortmaterial relativ einfach war und die Kinder so trotz ihrer allgemein schlechten Rechtschreibleistung ungefähr 50-60% der Wörter richtig schreiben konnten. Für richtig geschriebene Wörter konnten wir eine ähnliche LPC-Erhöhung feststellen, wie in der TE und iLS Gruppe. Für falsch geschriebene Wörter zeigte sich keine Erhöhung der EKP-Welle, was auf fehlende orthografische Repräsentationen für diese Wörter hindeutet. Demnach passen Kinder mit einer Rechtschreibstörung ihre Wortlesestrategie in

Abhängigkeit davon an, ob sie für das präsentierte Wort über einen orthografischen Eintrag verfügen oder nicht. Eine weiterführende Diskussion hierzu findet sich in der ersten beigelegten Veröffentlichung (Bakos et al., 2018) der vorliegenden kumulativen Dissertation.

Zusammenfassend legen die Ergebnisse nahe, dass die beeinträchtigte Lesegeschwindigkeit bei Kindern mit isolierten Lesestörungen auf einen verlangsamten lexikalischen Zugriff zurückzuführen ist, während Rechtschreibprobleme durch (zumindest teilweise) fehlende orthografische Repräsentationen begründet sind.

Studie 2 hatte das Ziel, die Automatisierung von Buchstabe-Laut-Beziehungen in Lese-Rechtschreibstörungen zu untersuchen. Eine effiziente und schnelle Zuordnung von Buchstaben zu Sprachlauten spielt sowohl für sublexikalische Prozesse, als auch im späteren

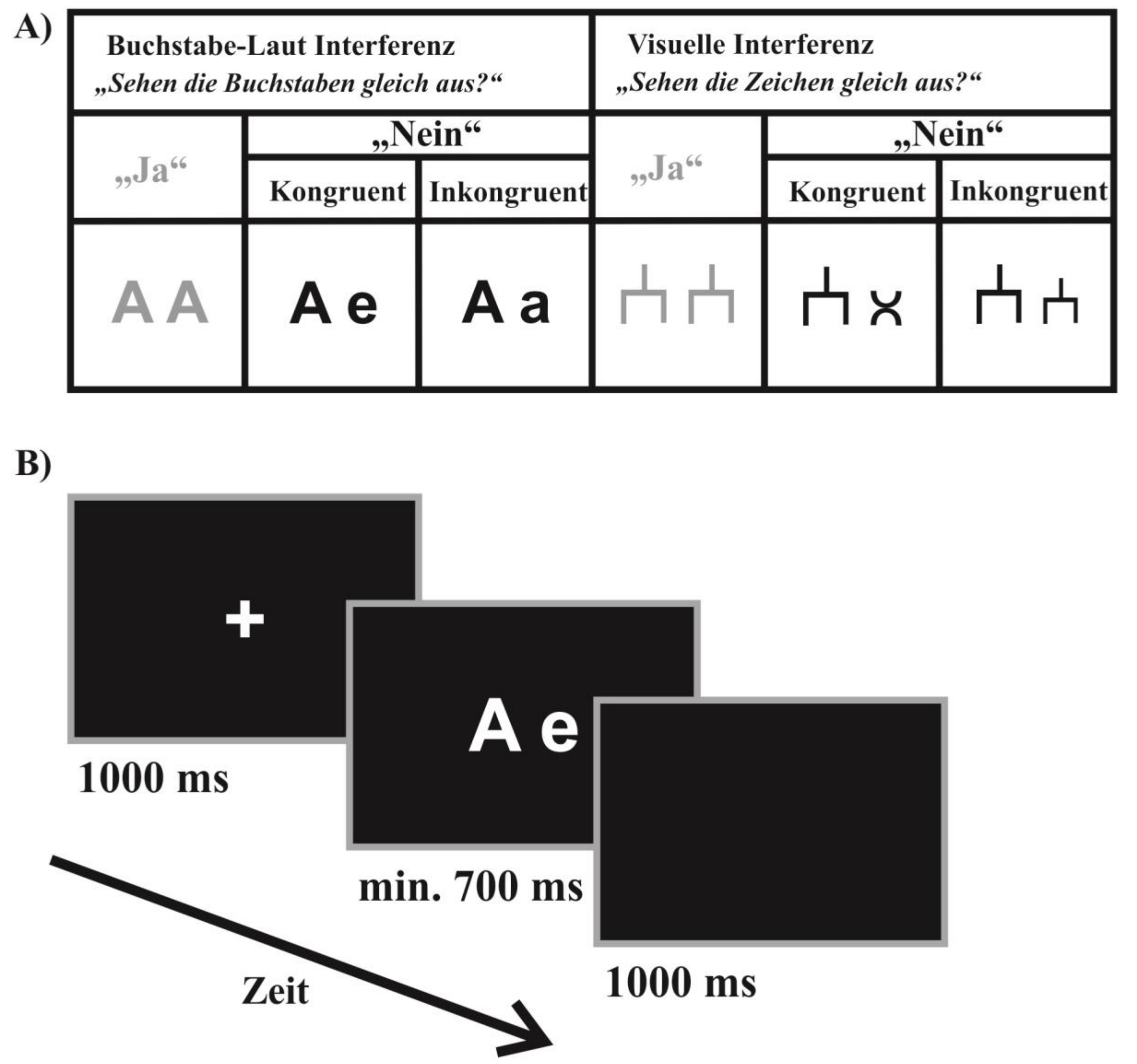

Abbildung 3. Buchstabe-Laut und visuelle Interferenz Paradigma. (A) Die experimentellen Bedingungen mit jeweils einer Beispielitem. (B) Exemplarische Darstellung eines Trials. Die Teilnehmer wurden gebeten, per Tastendruck zu entscheiden, ob die zwei Buchstaben (oder Zeichen) gleich aussahen oder nicht.

Leseerwerb für lexikalische Prozesse eine wichtige Rolle. Dazu wurde ein neues EEG-Paradigma entwickelt und zunächst bei zwei Gruppen von Kindern analysiert: Bei einer Gruppe von Kindern mit LRS (n=36) und bei einer Gruppe typisch entwickelter (TE) Kinder (n=37). Die Auswertung der Daten zu iRS und iLS ist im nächsten Schritt geplant, in Zusammenarbeit mit den Projektkooperationspartnern von der Karl-Franzens-Universität Graz. Die Aufgabe der Kinder bestand darin, zwei Buchstaben (oder zwei Zeichen) visuell miteinander zu vergleichen (siehe Abbildung 3). In der inkongruenten Bedingung, wo die zur Verfügung stehenden Informationen in Widerspruch zueinanderstanden (*gleiche/r* Phonologie/Sprachlaut bei *ungleicher* visueller Form – z.B.: **A a**), haben wir einen kognitiven Konflikt erwartet, vorausgesetzt dass die Verbindung zwischen Buchstaben und Lauten hoch automatisiert und der phonologischer Zugriff schnell ist. Die kongruente Bedingung (*ungleiche/r* Phonologie/Sprachlaut bei *ungleicher* visueller Form – z.B.: **A e**) sollte im Gegensatz dazu zu keinem kognitiven Konflikt führen (siehe Abbildung 3). Der Konflikt in der inkongruenten Bedingung wurde in den Komponenten N1 (70-140 ms), N2 (280-380 ms) und cSP (500-900 ms; conflict slow potential) abgebildet.

Die Ergebnisse zeigten eine verringerte Automatisierung der Buchstabe-Laut-Verbindungen in der LRS Gruppe verglichen mit der TE Kontrollgruppe, gespiegelt in der fehlenden Modulierung der EKP-Wellen N1 und cSP durch Inkongruenz. In der TE Gruppe zeigte sich

Tabelle 2. Auflistung der Ergebnisse von Studie 2.

Buchstabe-Laut Interferenz	**TE**	**LRS**
Genauigkeit	Kongr. > Inkongr.	Kongr. > Inkongr.
Reaktionszeiten	Kongr. < Inkongr.	Kongr. < Inkongr.
N1	Kongr. > Inkongr.	Kongr. = Inkongr.
N2	Keine Unterschiede	
cSP	Kongr. < Inkongr.	Kongr. = Inkongr.
Visuelle Interferenz	**TE**	**LRS**
Genauigkeit	Kongr. > Inkongr.	Kongr. > Inkongr.
Reaktionszeiten	Kongr. < Inkongr.	Kongr. < Inkongr.
N1	Keine Unterschiede	
N2	Kongr. > Inkongr.	Kongr. > Inkongr.
cSP	Kongr. < Inkongr.	Kongr. < Inkongr.

eine Verminderung der N1 und eine Erhöhung der cSP-Amplitude zu inkongruenten Buchstabenpaaren (z.B.: **A a**) im Vergleich zu kongruenten Buchstabenpaaren (z.B.: **A e**), während in der LRS Gruppe keine Unterschiede feststellbar waren (für die Auflistung der Ergebnisse siehe Tabelle 2). Im visuellen Kontrollexperiment, wo Zeichen miteinander verglichen werden mussten, waren die Inkongruenz-bedingten Effekte gleich stark in beiden Gruppen (siehe auch Tabelle 2). Dies lässt darauf schließen, dass langsame Worterkennung bei LRS möglicherweise durch fehlende Automatisierung der Buchstabe-Laut-Zuordnungen erklärt werden kann. Diese Probleme bei der Zuordnung resultieren allerdings nicht aus Problemen der visuellen Verarbeitung, da im Experiment mit visuellen Zeichen kein Unterschied zwischen der TE und der Störungsgruppe feststellbar war.

Interessanterweise gab es keine Unterschiede zwischen den Gruppen in den Verhaltensdaten. Die Reaktionszeiten und die Genauigkeitsraten waren sowohl in der TE als auch in der LRS Gruppe besser in der kongruenten als in der inkongruenten Bedingung. Dies zeigt die Wichtigkeit neurophysiologischer Messungen, insbesondere bei schnellen Verarbeitungsprozessen; aufgrund der Verhaltensdaten alleine hätte man die Unterschiede zwischen den beiden Gruppen in der phonologischen Verarbeitung nicht aufgedeckt. Eine weiterführende Diskussion hierzu findet sich in der zweiten beigelegten Veröffentlichung (Bakos et al., 2017) der vorliegenden kumulativen Dissertation.

Zusammenfassende Diskussion und Ausblick

In der vorliegenden Dissertation wurden lexikalische und sublexikalische Worterkennungsprozesse bei Kindern mit Lese- und/oder Rechtschreibstörung auf der neurophysiologischen Ebene mittels EEG untersucht. Es konnte gezeigt werden, dass Lesegeschwindigkeitsdefizite bei Kindern mit einer isolierten Lesestörung höchstwahrscheinlich auf einen verlangsamten orthografisch-lexikalischen Zugriff zurückzuführen sind. Des Weiteren zeigt die vorliegende Dissertation, dass Kinder mit einer isolierten Lesestörung über intakte orthografische Repräsentationen verfügen, was auch auf der neurophysiologischen Ebene feststellbar ist.

Kinder mit einer Rechtschreibstörung verfügen im Gegensatz dazu nur teilweise über orthografische Repräsentationen. Die vorliegende Dissertation untersuchte zum ersten Mal lexikalisch-orthografische Prozesse in Abhängigkeit des individuellen, aktuellen, item-spezifischen Wissens. Neurophysiologische Marker des orthografischen Abrufs waren nur bei richtig geschriebenen Wörtern zu entdecken, fehlten hingegen bei falsch geschriebenen Wörtern.

	Januar	Februar	März	April	Mai	Juni	Juli	August	September	Oktober	November	Dezember
2014									Vorbereitung der Screening, Kontaktaufnahme mit Schulen			
2015	Vorbereitung der Screening, Kontaktaufnahme mit Schulen				Screening, Einladungen für individuelle Testungen							
			Vorbereitung der Experimente, Pilotierung (Testreihe 1)				individuelle Verhaltens- und EEG-Testungen (Testreihe 1)					
2016	Datenverarbeitung, Datenauswertung, Publikation der Ergebnisse (Testreihe 1)											
		Vorbereitung der Experimente, Pilotierung (Testreihe 2)				individuelle Verhaltens- und EEG-Testungen (Testreihe 2)						
2017	Datenverarbeitung, Datenauswertung, Publikation der Ergebnisse (Testreihe 2)											

Abbildung 4. Zeitlicher Rahmen und Ablauf des Projektes „UsLeR“.

Des Weiteren leistete die vorliegende Dissertation einen wichtigen Schritt zum Verständnis von sublexikalischen Problemen in Lese-Rechtschreibstörungen durch das Implementieren eines neuen EEG-Paradigmas. Bei Kindern mit kombinierten Lese-Rechtschreibstörungen konnte dadurch eine verminderte Automatisierung der Buchstabe-Laut-Verknüpfungen gezeigt werden. Aufbauend auf diesem Befund wird im nächsten Schritt überprüft, ob sublexikalische Prozesse in isolierten Störungen in der gleichen Weise beeinträchtigt sind.

Die Frage, ob die lexikalischen und sublexikalischen Beeinträchtigungen der Worterkennung bei Lese- und/oder Rechtschreibstörungen eine Entwicklungsverzögerung oder eine dauerhafte Beeinträchtigung darstellen, bleibt allerdings weiterhin ungeklärt. Die vorliegende kumulative Dissertation untersuchte eine homogene Altersstichprobe und liefert daher Befunde nur zu einem Ausschnitt des Entwicklungsverlaufs. Weiterführende Längsschnitt-Studien sind daher notwendig, um den Entwicklungsaspekt zu berücksichtigen. Trotz dieser weiteren Fragen trägt die vorliegende Dissertation wesentlich zum besseren Verständnis der isolierten Lese- und Rechtschreibstörungen bei und zeigt, wie kognitive Neurowissenschaften Störungstheorien unterstützen können.

Darstellung des eigenen Beitrags

Das Forschungsprojekt „Ursachen spezifischer Probleme im Lesen oder Rechtschreiben (UsLeR)“, aus dem die vorliegende kumulative Dissertation hervorging, wurde in Zusammenarbeit mit dem Institut für Psychologie der Karl-Franzens-Universität Graz von der Deutschen Forschungsgemeinschaft (DFG) und dem Österreichischen Wissenschaftsfond FWF (Fonds zur Förderung der wissenschaftlichen Forschung) von 01.04.2015 bis 31.03.2018 gefördert. Das gemeinsame Projekt wurde von Prof. Dr. Karin Landerl, PD Dr. Kristina Moll und Prof. Dr. Gerd Schulte-Körne initiiert. PD Dr. Kristina Moll leitete und supervidierte das Projekt und meine Arbeit in München. Prof. Dr. Schulte-Körne supervidierte meine Dissertation im Rahmen des Projekts.

Zu Beginn meiner Promotion (01.04.2015) stand das Studiendesign schon fest (siehe auch Abbildung 4). Das Votum der Ethik-Kommission zur ethisch-rechtliche Unbedenklichkeit der Studie lag ebenfalls bereits vor. Meine Aufgaben in dem Projekt beinhalteten neben der Entwicklung der Stimuli und der Programmierung der experimentellen Paradigmen auch das Screening der Kinder auf Lese-Rechtschreibstörungen in Schulen, die Probandenrekrutierung und die individuellen Verhaltenstestungen und Ableitungen der EEG-Messungen. Das Screening, die individuellen Testungen und die Probandenrekrutierung wurden außerdem durch Studienassistentinnen und studentische Hilfskräfte unterstützt. Die Aufbereitung und Auswertung der EEG-Daten führte ich selbstständig durch, wobei Dipl.-Phys. Jürgen Bartling mich bei technischen Fragen unterstützte. Die beiden Fachartikel wurden von mir selbstständig verfasst und nach Rückmeldung der Koautoren überarbeitet und publiziert.

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ABKÜRZUNGSVERZEICHNIS

Deutsch	
EEG	Elektroenzephalogramm
EKP	ereigniskorrelierte Potential
illegPW	illegales Pseudowort
iLS	isolierte Lesestörung
iRS	isolierte Rechtschreibstörung
legPW	legales Pseudowort
LPC	Late Positive Complex
LRS	Lese-Rechtschreibstörung
PH	Pseudohomophone
TE	typisch entwickelt
VWFA	Visuelles Wortformareal
W	Wort

Englisch	
EEG	electroencephalogram
ERP	event-related potential
iRD	isolated reading disorder
iSD	isolated spelling disorder
LPC	late positive complex
RSD	reading-spelling disorder
TD	typically developing

STUDIE1:

Neurophysiological correlates of word processing deficits in isolated reading and isolated spelling disorders

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Neurophysiological correlates of word processing deficits in isolated reading and isolated spelling disorders

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HIGHLIGHTS

- Orthographic processing was assessed with EEG in isolated reading and isolated spelling disorders.
- Reading and spelling deficits are associated with different neurophysiological deficit profiles.
- In spelling disorders, neurophysiological word processing is moderated by item specific knowledge.

ABSTRACT

Objective: In consistent orthographies, isolated reading disorders (iRD) and isolated spelling disorders (iSD) are nearly as common as combined reading-spelling disorders (cRSD). However, the exact nature of the underlying word processing deficits in isolated versus combined literacy deficits are not well understood yet.
Methods: We applied a phonological lexical decision task (including words, pseudohomophones, legal and illegal pseudowords) during ERP recording to investigate the neurophysiological correlates of lexical and sublexical word-processing in children with iRD, iSD and cRSD compared to typically developing (TD) 9-year-olds.
Results: TD children showed enhanced early sensitivity (N170) for word material and for the violation of orthographic rules compared to the other groups. Lexical orthographic effects (higher LPC amplitude for words than for pseudohomophones) were the same in the TD and iRD groups, although processing took longer in children with iRD. In the iSD and cRSD groups, lexical orthographic effects were evident and stable over time only for correctly spelled words.
Conclusions: Orthographic representations were intact in iRD children, but word processing took longer compared to TD. Children with spelling disorders had partly missing orthographic representations.
Significance: Our study is the first to specify the underlying neurophysiology of word processing deficits associated with isolated literacy deficits.
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1. Introduction

In English speaking countries, developmental dyslexia (DD) is primarily defined as a reading disorder which is characterized by deficits in word reading accuracy, that are frequently accompanied by spelling problems. The association between reading and spelling deficits is in line with theories of literacy development that generally assume a close, bidirectional relationship between reading and spelling development (e.g. Frith, 1985), with correlation scores of 0.77–0.86 between the two domains (for a review see Ehri, 1997). However, in consistent orthographies like German, reading accuracy is close to ceiling after one year of reading instruction, even in poor readers (Wimmer, 1993). Therefore, in consistent orthographies, reading problems are characterized by deficits in reading fluency rather than in reading accuracy.

Considering reading fluency as the relevant measure of reading, associations between reading and spelling skills are lower (correlation of 0.59–0.65, e.g. Wimmer and Mayringer, 2002) than reported in studies analyzing the association between reading accuracy and spelling. Furthermore, prevalence studies including reading fluency assessments have identified a substantial number of children, who have deficits in one literacy domain only. Thus, isolated deficits in reading (4–6%) and isolated deficits in spelling (3–5%) are

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nearly as common as combined reading-spelling deficits (7–8%), at least in consistent orthographies (Moll and Landerl, 2009; Wimmer and Mayringer, 2002). Children with isolated reading disorders (iRD) are characterized by accurate but dysfluent reading and age-appropriate spelling skills; whereas children with isolated spelling disorder (iSD) show the opposite pattern with age-appropriate reading skills, but poor performance in spelling tasks. This implies a double dissociation between reading (fluency) and spelling.

To explain reading fluency deficits in spite of accurate spelling, Wimmer and Mayringer (2002) assumed a phonological speed deficit in iRD. German is consistent in the reading direction, but rather inconsistent in the spelling direction. Thus, in order to spell a word correctly, word specific representations are required. As spelling is unimpaired in children with iRD, they must have built-up word specific orthographic representations. This assumption is supported by findings showing faster reading times for words, compared to pseudohomophones (i.e. misspelled words with the same phonological form, as for example rane instead of rain) in children with iRD. This indicates that word-specific orthographic representations are available, leading to faster recognition of words compared to pseudohomophones (Moll and Landerl, 2009). Thus, slow reading speed can most probably be explained by low phonological efficiency and slowed-down visual-verbal access in sublexical and lexical word processing. In line with this idea, children with reading disorders (iRD and combined reading-spelling disorder; cRSD) show marked problems in rapid automatized naming tasks (RAN), where children are asked to name rows of stimuli as quickly as possible (i.e. letters, digits, objects or colors). Performance in RAN tasks has been shown to be highly correlated with reading fluency (Wimmer and Schurz, 2010).

In contrast, children with iSD might have problems in building-up word specific representations as evident from their incorrect word spellings. In German speaking children (after 1–2 years of schooling), these misspellings are mostly phonologically correct but orthographic markers are disregarded resulting in orthographically incorrect spellings (e.g., "Munt" instead of "Mund (mouth)", which are pronounced identically in German). Frith (1985) proposed that iSD may result from underspecified orthographic representations which are sufficient for accurate and fast word recognition during reading (partial cue reading), but are insufficient for accurate spelling. Alternatively, children with iSD might compensate their deficit in building-up word specific representations by using sublexical decoding strategies during reading (e.g. letter-by-letter reading; Moll and Landerl, 2009). This compensatory mechanism is successful in orthographies with consistent letter-sound-correspondences like German.

Taken together, isolated reading deficits might result from a slowed-down lexical access, whereas isolated spelling deficits might reflect underspecified orthographic representations. Differentiation between these processing deficits requires measurement techniques with a high temporal resolution, such as electroencephalography (EEG). However, studies examining the neurophysiology of word processing deficits in isolated disorders are still missing. Furthermore, the question whether the neurophysiological profile of isolated disorders (e.g. only reading vs. only spelling deficits) differs from those of the combined disorder (both reading and spelling deficits) is unresolved. For this reason, we implemented a phonological lexical decision task (PLD-task) combined with EEG and assessed four experimental groups; a group of typically developing (TD) children, a group of children with cRSD, a group of children with iRD and a group of children with iSD.

The phonological lexical decision task (PLD-task) is a well-established task to investigate orthographic and phonological processing during reading (Hasko et al., 2013, 2014; Kronbichler et al., 2007; Schurz et al., 2010; van der Mark et al., 2009; Wimmer et al., 2010). In the current study, we presented words (Ws), pseudohomophones (PHs; derived from the words), legal pseudowords (legPWs; pseudowords following German orthographic rules) and illegal pseudowords (illegPWs; pseudowords violating German orthographic rules). The task of the participant was to indicate whether the visually presented stimulus sounds like a real word. Ws (e.g. rain, German example: "Mund") and PHs (e.g. rane, German example: "Munt") required a "yes" answer, whereas legPWs (e.g. hain, German example: "Munk") and illegPWs (e.g. hasz, German example: "Mukk") required a "no" answer. The comparison of Ws and PHs is thereby indicative of orthographic processing at the lexical level, because orthographic representations are only stored for real words (Ziegler and Goswami, 2005). The advantage of comparing Ws and PHs instead of using a lexical decision task comparing Ws and PWs is thereby that Ws and PHs differ only in orthography but share the same phonology. Thus, any difference between Ws and PHs is due to their difference in orthographic representations and is not influenced by phonological effects. The comparison of legPWs and illegPWs is indicative of orthographic processing at the sublexical level. Sublexical orthographic sensitivity can be interpreted in the context of a general sensitivity to orthographic rules and to permissible letter patterns of a language (Ziegler and Goswami, 2005). Comparing Ws vs. PHs and legPWs vs. illegPWs separately from each other has furthermore the advantage, that "yes" and "no" answer trials do not get intermixed in the analysis, which is an important methodological improvement to previous ERP studies using the PLD-task (e.g. Hasko et al., 2013).

Another innovation of the current study is that we have assessed spelling performance for the experimental word material used in the ERP-measurements. Therefore, we had the possibility to analyze ERP components separately for correctly and incorrectly spelled words for each individual. This item-based analysis can provide valuable information, because even the poorest speller is likely to have intact orthographic representations for at least some of the words used in the experiment. Thus, differentiating between correctly and incorrectly spelled words can help to specify the neurophysiological pattern related to lexical orthographic processing deficits in children with spelling disorder.

The most commonly examined reading-related ERP components, which can be observed in the PLD-task are the N170, the N400 and the late positive complex (LPC).

The N170 (also called N1) is a left lateralized component, measured around 170 ms after stimulus onset over occipito-temporal brain regions (Bentin et al., 1999; Maurer et al., 2005a, 2005b). The N170 amplitude has been found to be higher for letter strings than for symbol strings; thus, the N170 component is commonly interpreted in the context of print sensitivity, reflecting the expertise of skilled readers with visual word-like stimuli. However, it is still not clear whether the N170 is also sensitive to familiar orthographic material (e.g. words) when compared to unfamiliar orthographic material (e.g. pseudohomophones or pseudowords). There is evidence for an enhanced N170 for unfamiliar words or pseudowords compared to familiar words, however, not all studies confirmed this effect (for a review see Maurer and McCandliss, 2008). The findings are also inconclusive with respect to sublexical orthographic sensitivity: One study reported higher N170 amplitudes for atypical compared to typical items (Hauk et al., 2006), whereas Araújo et al. (2012, 2015) found the opposite pattern or no difference between conditions. Thus, findings on word familiarity effects on the N170 are still inconclusive.

The N400 is commonly measured over centro-parietal areas as a relative negativity, peaking around 400 ms. Previous studies suggest that the N400 is related to the meaning of the presented item and thus might be interpreted as an index of semantic memory (for reviews see Kutas and Federmeier, 2011; Münte et al., 2000). However, findings are inconclusive as to whether this component is also sensitive to orthographic familiarity. In visual lexical decision tasks (i.e. the question "Is ... an existing word?"), the N400 has been found to be smaller for orthographically familiar words than for unfamiliar word stimuli (Braun et al., 2006; Briesemeister et al., 2009). However, in PLD-tasks, there were no differences between the N400 amplitudes of words, pseudohomophones and pseudowords (Hasko et al., 2013, 2014), which is in line with the interpretation that the N400 is reflecting semantic memory. In the PLD-task, semantic processing of the stimulus might not be required for task solution, as the question to be answered is rather related to the phonology ("Does ... sound as an existing word?").

The late positive complex (LPC; also called P600 or parietal P3) is thought to reflect word recognition memory, as it is higher for old (learned) words compared to new words (for a review see Rugg and Curran, 2007). This word recognition effect has been related to access to the phonological lexicon (Hasko et al., 2013) and to orthographic word knowledge (Balass et al., 2010). The LPC is commonly measured between 500 and 800 ms over left centro-parietal areas (e.g. van Strien et al., 2009).

With respect to dyslexia, there are only two studies which have reported ERP-findings using a PLD-task. Hasko et al. (2013) did not find any differences between dyslexic and TD children in their absolute N170 amplitudes, even though print sensitivity measured as the difference between the N170 of non-linguistic (false fonts) and linguistic material was higher in the TD group than in the dyslexic group. Furthermore, Hasko et al. (2013, 2014) reported "nearly absent" N400 amplitudes and missing LPC word recognition effects in children with dyslexia, in contrast to the more negative N400 and clear LPC word recognition effect of TD 8-year-olds.

Thus, based on Hasko et al.'s (2013, 2014) findings, we can conclude that there might be neurophysiological differences between TD children and children with dyslexia, in the processing of word material, both in the early (N170) and a later time window (LPC). However, the neurophysiological correlates of orthographic processing in isolated reading and spelling disorders have not been examined yet. We implemented a PLD-task in groups of 9-year-old children with combined reading-spelling disorder (cRSD), isolated reading disorder (iRD) and isolated spelling disorder (iSD), and in a group of TD children to explore this question. Our sample had three years of formal reading instruction, thus, we expected them to have built-up orthographic representations for a considerably big number of words, occurring frequently in children's text books, which is ideal for our study.

In detail, we were interested in answering the following questions: (For an overview of our hypothesis please see Table 1.)

(1) Are there differences in the neurophysiology (N170, N400, and LPC) of lexical word-processing between children with cRSD, iRD and iSD compared to TD children?

This question can be answered by comparing Ws and PHs, as we expect that only Ws but not PHs have an entry in the orthographic lexicon. We hypothesize that TD children have built-up orthographic representations for the frequent and easy words that we have presented in our experiment and that they have a fast and efficient access to these word specific representations. However, given that previous findings were inconclusive on whether the N170 is sensitive to familiar orthographic material when compared to unfamiliar orthographic material; it is unclear whether neurophysiological differences between Ws and PHs might already occur in an early time window (N170) or whether this difference might only be evident in later time windows (LPC).

Children with iRD are expected to have intact orthographic representations, but a slowed-down access to them, which might lead to delayed neurophysiological effects compared to the TD group. Thus, differences between Ws and PHs are only expected in a late time window for this group. However, in the late component, the iRD group should show similar effects as the TD group (higher LPC for Ws than PHs).

Children with iSD and cRSD are expected to have deficient or missing orthographic representations, thus, we do not expect to see neurophysiological differences between the W and PH conditions, neither in the early N170, nor in the late component (LPC).

(2) Are there differences between children with cRSD, iRD and iSD compared to TD children in sublexical orthographic sensitivity as indicated by the neurophysiology (N170, N400) of pseudoword processing?

This question can be answered by comparing legPWs and illegPWs, as only illegPWs in contrast to legPWs contain sublexical elements which violate German orthography and are thus indicative of orthographic sensitivity. We expect to find similar group effects for the legPW-illegPW comparison as described above for the W-PH comparison (see also Table 1). TD children are expected to show effects of sublexical orthographic sensitivity relatively early, most probably already in the N170. These effects might not be evident in the iRD group because of slow processing, and might be absent in the cRSD and iSD groups because of their poor orthographic skills. Given that there are no orthographic representations for PWs and the LPC reflects word recognition memory, the LPC was of no interest for this comparison.

(3) Are lexical orthographic word processing differences between spelling impaired (cRSD and iSD) and TD groups related to the orthographic knowledge of a word? More precisely; is the underlying neurophysiology (LPC) of lexical word-processing the same for correctly and incorrectly spelled words in children with spelling disorder?

This question is going to be answered by an item-based analysis comparing the neurophysiological pattern for correctly versus incorrectly spelled words in children with spelling disorders (cRSD, iSD). We assume that lexical word processing difficulties (e.g. no difference between Ws and PHs in the LPC component) might be more distinct in incorrectly spelled words and less distinct or absent in correctly spelled words. In correctly spelled words, lexical orthographic effects might lead to an enlarged LPC for Ws compared to PHs even in poor spellers, as correct spelling requires the built-up of orthographic representations.

Table 1
Hypothesis (for research questions 1 and 2) for each ERP component.

	N170: Print sensitivity	N400: Semantic processes	LPC: Lexical orthographic processes
Main effect condition	Ws∼ = PHs legPWs∼ = illegPWs	–	Ws > PHs
Main effect group	–	TD, iRD > cRSD, iSD	–
Condition × group interaction	Ws∼ = PHs, legPWs∼ = illegPWs only in TD, but not in cRSD, iRD or iSD groups	–	Ws > PHs in TD and iRD groups, but not in cRSD and iSD groups

2. Material and methods

2.1. Participants

The experiment was part of a project examining cognitive profiles and neurophysiological correlates of children with different literacy profiles. The selection criteria described here are the same as reported in the study by Bakos et al. (2017): "Children were selected based on an extensive classroom screening including 1488 children at the end of 3rd Grade. The screening was carried out in 46 primary schools in the suburban and urban areas of Munich (Germany). Reading fluency and spelling were assessed by standardized classroom tests (SLS 2–9: Wimmer and Mayringer, 2014; DRT-3: Müller, 2003). Children were classified as reading and spelling impaired (combined reading-spelling disorder group; cRSD) if they scored below the 20th percentile on the reading screening test and below or at the 20th percentile on the spelling test. To be included in the isolated reading or isolated spelling disorder group, children had to score above the 25th percentile in the unaffected literacy domain (spelling or reading). Children with reading and spelling performances between the 25th and 75th percentile qualified for the control TD group" (see Bakos et al., 2017).

Given that reading in the classroom could only be assessed by a screening test measuring silent reading, reading scores were validated by an individually administered one-minute word and pseudoword reading fluency test (SLRT-II: Moll and Landerl, 2013) during individual testing. Children in the cRSD or iRD group were excluded from further testing, if they did not score below the 20th percentile on at least one subtest (word- or pseudoword reading) of the individually administered reading measure (SLRT-II).

In addition, we assessed nonverbal IQ (CFT 20-R: Weiß, 2006) and included only children with an IQ at or above 85 in the final sample. "Further inclusion criteria were German as 1st language, normal or corrected-to-normal vision, absence of neurological deficits, and no symptoms of AD(H)D as measured by a standardized questionnaire answered by caregivers (DISYPS-II: Döpfner et al., 2008)" (see Bakos et al., 2017).

Hundred-twenty-six children (40 TD children, 39 children with cRSD, 22 children with iRD and 25 children with iSD) fulfilled these criteria, and were willing to participate in the PLD-task. Although the cutoff criterion for reading and spelling was rather lenient ($\leq$20st percentile), 76 children out of 86 with a reading and/or spelling disorder fulfilled diagnostic criteria for dyslexia (i.e. scoring at least one standard deviation below the population mean on a standardized reading or spelling test together with converging evidence from school reports or academic history). Based on task performance and EEG quality, we excluded 4 TD children (1 child with incomplete EEG measurement and 3 children based on low-number of artifacts-free ERP segments), 6 children with cRSD (3 children based on their low accuracy level and 3 children based on their EEG data, i.e. 1 child with incomplete EEG measurement and 2 children based on low number of artifacts-free ERP segments), 1 child with iRD (based on low number of artifacts-free ERP segments), and 4 children with iSD (2 children with incomplete EEG measurement and 2 children based on low number of artifacts-free ERP segments).

This procedure resulted in a final sample size of 111 children: 36 children in the TD group, 33 children in the cRSD group, 21 children in the iRD group and 21 children in the iSD group. There were no significant differences between the groups in age, intelligence, gender or handedness (all $ps > .07$; see Table 2).[1] However, in line with our selection criteria the groups differed in reading speed and spelling performance (all $ps < .001$; see Table 2). Post-hoc tests revealed that reading performance (SLS 2–9) was significantly higher in the TD and iSD group than in the cRSD (both $ps < .001$) and iRD group (both $ps < .001$). There was no difference in reading speed between the cRSD and iRD group ($p = .95$) and between the iSD and TD group ($p = .09$). With respect to spelling performance, both the TD and iRD group outperformed the cRSD and iSD group (all $ps < .001$). There was no difference between the cRSD and iSD group in their spelling skills ($p = .06$). Although spelling scores were lower in the iRD than in the TD group ($p < .001$), the iRD group scored clearly within the normal range (percentile ranks between 28 and 74).

The study was performed in accordance with the latest version of the Helsinki declaration and in compliance with national legislation. The study was approved by the institutional review board of the local ethics committee. Parents and children were informed about the aims of the study and the experimental procedures, and gave their written consent prior to inclusion in the study. Children received vouchers in return for their participation.

2.2. Behavioral and cognitive measures

2.2.1. Screening in classroom settings

All screening measures (SLS 2–9, DRT-3 and CFT-20-R) were assessed in the classroom at the end of grade 3 by trained research assistants.

2.2.1.1. Reading speed. In the reading fluency screening test (SLS 2–9: Wimmer and Mayringer, 2014; parallel-test reliability $r = 0.95$ and content validity $r = 0.89$ for grade 2), children were asked to read sentences silently as fast as possible and to judge them as semantically correct or incorrect (e.g., "Trees can speak"). After three minutes the task was terminated and reading scores were calculated based on the number of correctly marked sentences.

2.2.1.2. Spelling. In the standardized spelling test (DRT-3: Müller, 2003; parallel-test reliability $r = 0.92$ and content validity $r = 0.78$) 44 single words were dictated and children were asked to write them into sentence frames. Spelling scores were calculated based on the total number of correct word spellings. One participant with cRSD did not take part in the screening but volunteered for participation during the individual testing phase at the beginning of Grade 4. Therefore, we adapted the spelling test for this child and assessed spelling by the corresponding version of the DRT-3 for Grade 4 (DRT-4: Grund et al., 2004; split-half reliability $r = 0.92$ and content validity $r = 0.68–0.94$).

2.2.1.3. General cognitive abilities. We implemented the German version of the Culture Fair Intelligence Test (CFT-20-R; Weiß, 2006). The CFT-20-R is designed to estimate nonverbal IQ without the influence of sociocultural and environmental factors. It comprises of four subtests: Series, Classification, Matrices and Topology and has a high reliability ($r = 0.92–0.96$) and construct validity (correlation with the "g"-factor $r = 0.78–0.83$).

2.2.2. Individual assessments

Individual testing was part of a large cognitive and neurophysiological test battery and took place on two or three different days. The maximum time interval between the behavioral assessment (including the spelling of the experimental word material) and the EEG experiment was 96 days (mean: 19.86 days).

2.2.2.1. Word- and pseudoword reading. Word and nonword reading fluency was assessed by an individually administered one-minute-fluent word- and pseudoword-reading test (SLRT-II;

[1] Group differences in intelligence were marginally significant ($p = .07$). However, including IQ as a covariate did not change main findings. We therefore reported the analyses without including IQ as covariate.

Table 2
Descriptive statistics of the groups and between group comparisons.

	TD group (N = 36)	cRSD group (N = 33)	iRD group (N = 21)	iSD group (N = 21)	*F-value*	*p-value*
Age in month	113.94 (4.68)	114.21 (6.06)	115.10 (4.66)	115.71 (5.11)	0.64	.59[1]
IQ[a]	109.86 (10.19)	110.09 (13.05)	114.86 (14.23)	104.76 (11.18)	2.44	.07[1]
Handedness[b] (left/right)	4/32	2/31	4/17	1/20		.36[2]
Gender (females/males)	19/17	17/16	11/10	8/13		.71[2]
Reading speed[c]	52.55 (12.67)	9.99 (9.17)	9.80 (4.41)	47.59 (12.89)	133.94	.00[1]
Spelling[d]	58.14 (11.65)	9.45 (6.15)	43.88 (12.69)	14.57 (5.43)	185.01	.00[1]
SLRT-II words[e]	54.33 (17.01)	8.02 (6.39)	12.67 (7.55)	39.26 (16.87)	88.64	.00[1]
SLRT-II pseudowords[e]	52.54 (19.62)	13.56 (9.91)	14.21 (6.45)	41.71 (23.41)	43.97	.00[1]

[a] Based on CFT-20-R.
[b] Based on self-report.
[c] Based on SLS 2–9. Reported in percentile ranks.
[d] Based on DRT-3 or DRT-4. Reported in percentile ranks.
[e] Reported in percentile ranks.
[1] One-way repeated measures ANOVA.
[2] Pearson's chi-square test.

Moll and Landerl, 2013; parallel-test reliability r = 0.90–0.94 and content validity r = 0.69–0.85 for grade 3). Children had to read aloud a list of words and a list of pseudowords as fast as possible without making errors. The relevant measure was the number of correctly read words and pseudowords read within the one minute time limit.

2.2.2.2. DYSIPS-II. A telephone interview was conducted with one of the participant's caregiver in order to exclude children with attentional problems. The interview was based on the ADHD questionnaire of the DISYPS-II (Döpfner et al., 2008), which is a well-established standardized structured interview for psychiatric disorders in children and adolescents based on DSM-IV and ICD-10 guidelines (Cronbach's Alpha = 0.87–0.94 for parental ratings of ADHD symptoms). The ADHD-questionnaire of the DISYPS-II consists of 20 questions that cover the three main dimensions of ADHD symptomatology: attentional deficits, hyperactivity and impulsivity.

2.2.2.3. Spelling of the experimental word material. Spelling of the experimental word material was assessed in addition to the EEG experiment and took place on a different day before the neurophysiological measurement. The 80 experimental words were dictated in sentence frames.

2.3. ERP paradigm and procedure

During ERP acquisition, children performed a phonological lexical decision (PLD) task. The task of the child was to indicate by button press whether the visually presented stimulus sounded like a real word ("Does ... sound like a real word?"). There were four types of experimental stimuli: words (Ws), pseudohomophones (PHs), legal pseudowords (legPWs) and illegal pseudowords (illegPWs). Ws and PHs sound like real words and therefore required a "yes" answer, whereas legPWs and illegPWs required a "no" answer. Ws were orthographically and phonologically familiar, real German words (e.g. "Mund", English example: rain). PHs were phonologically familiar, but orthographically unfamiliar word-like stimuli (e.g. "Munt", English example: rane). In contrast to Ws, (whole) word-specific, lexical orthographic representations do not exist for PHs. Thus, the comparison of Ws and PHs gives us insights about lexical orthographic sensitivity. PWs were both orthographically and phonologically unfamiliar, with an important difference between legPWs and illegPWs: IllegPWs (e.g. "Mukk", English example: hasz) contained in contrast to legPWs (e.g. "Munk", English example: hain) sublexical orthographic elements (i.e., letter-combinations), which violated German orthography. Thus, the comparison of legal and illegal PWs gives us insights about sublexical orthographic sensitivity in the groups.

There were 80 stimuli of each type (Ws, PHs, legPWs and illegPWs), thus there was a total amount of 320 stimuli. Every item was presented only once.

The words (Ws) were all high frequency words based on the childLex corpus (Schroeder et al., 2015) with a mean absolute frequency of 1537.80 for 9-to-10 year-old children. Forty of the 80 selected Ws were short (3–5 letters) and 40 of the Ws were long (6–9 letters). PHs were derived from these Ws by exchanging one phonologically identical grapheme. PWs were derived from Ws by exchanging one grapheme per syllable. W, PH and legPW lists were matched on the number of letters and on bigram- and trigram-frequencies according to childLex (see Table 3). As illegPWs contained illegal letter-combinations, which do not exist in German orthography, bigram- and trigram frequencies of the illegPWs were not matched to the other stimuli. However, the illegal PWs were matched to the other stimuli on the number of letters (see Table 3).

The total amount of 320 stimuli was divided into four blocks (80 stimuli per block). Each block presented 20 Ws, 20 PHs, 20 legPWs and 20 illegPWs. Ws and their corresponding PHs, legPWs and illegPWs were never presented in the same block. One block lasted about 6 min, thus, total presentation time was approximately 24 min.

Stimuli were presented intermixed in four pseudorandomized lists. The pseudo-randomization ensured that no more than four consecutive trials required the same answer ("yes" or "no"), preventing response tendencies. The presentation order of Ws and PHs, as well as the presentation order of the legal and illegal PWs was counterbalanced across lists. (In two of the lists Ws and legPWs preceded their PHs and illegPWs, whereas in the other two lists the presentation order was reversed: Ws and legPWs were presented after their corresponding PHs and illegPWs.) The four versions were randomly assigned to the participants within each group.

Before the experiment started, a practice block with both visual and verbal feedback (20 trials; 5 Ws, 5 PHs, 5 legPWs and 5 illegPWs) was completed. The stimuli presented in this practice block were not used in the experiment.

The stimuli were presented in white on black background in the center of a high resolution (1920 × 1080) 24-inch monitor (60 Hz refresh rate) using E-Prime® 2.0 software (Psychology Software Tools, Inc). Children were seated in front of the computer screen at a distance of 70 cm, which resulted in a vertical visual angle of 0.65–0.89° and in a horizontal visual angle of 1.37°–6.06° depending on the presented stimulus. The stimuli appeared in the middle of the screen and remained for at least 1000 ms or until response if

Table 3
Item characteristics for words (W), pseudohomophones (PH), legal pseudowords (legPW) and illegal pseudowords (illegPW).

	W		PH		legPW		illegPW			
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F-value*	*p-value*
Number of letters	5.54	1.61	5.71	1.74	5.54	1.61	5.85	1.54	0.69	.56[1]
Log bigram-frequency[a,b]	5.61	5.50	5.58	5.54	5.56	5.43			0.45	.64[1]
Log trigram-frequency[a,b]	4.72	4.79	4.69	4.87	4.59	4.73			0.92	.40[1]

[a] The logarithms of the bigram- and trigram-frequencies were compared between Ws, PHs and legPWs only, because illegPWs contained letter-combinations, which do not exist in German orthography.
[b] Based on ChildLex lexicon.
[1] One-way repeated measures ANOVA.

the response took longer than 1000 ms. This time setting was necessary to ensure that even the poorest reader had enough time to read the stimuli, but also to avoid offset effects on the EEG in good readers with reaction times below 1000 ms. The task of the child was to decide, whether the visually presented stimulus sounded like a real word by pressing the right button for "yes" and the left button for "no" on a two-key keyboard as fast as possible. Depending on the accuracy of the response, children received immediate feedback in form of a happy or a sad emoji. The feedback remained on the screen for 1500 ms. The next trial started after a 500 ms blank screen (see Fig. 1).

2.4. ERP recording and analysis

We recorded the continuous EEG with an Electrical Geodesics Inc. 128-channel system during testing (sampling rate: 500 Hz, reference: Cz; Electrical Geodesics Inc.; EGI, Eugene, OR; Tucker, 1993). An electrode of the Electrical Geodesics Inc. 128-channel system consists of a silver chloride-plated carbon-fiber pellet, which is connected to a gold-plated pin by a shielded wire. Impedance was monitored and kept below 50 kΩ throughout the recording. Further processing steps were performed with BrainVision Analyzer 2.0 (Brain Products GmbH, Gilching, Germany).

Preprocessing of the EEG-signal was similar to Bakos et al. (2017): "After visual inspection of the data, the continuous EEG was filtered (low cutoff: 0.5 Hz, time constant: 0.3, 12 dB/Oct; high cutoff: 40 Hz, 12 bB/Oct; notch filter: 50 Hz) and EOG artifacts were removed by semiautomatic ocular correction, using an ICA algorithm as implemented in BrainVision Analyzer 2.0 (Slope Mean, over the whole data, ICA with infomax algorithm, total squared correlations to delete: 30%; Gratton et al., 1983; Plank, 2013). Other artifacts were excluded automatically (gradient criteria: more than 50 μV difference between two successive data points or more than 100 μV difference in a 100 ms window; absolute amplitude criteria: amplitudes exceeding +150 μV or −150 μV; low activity criterion: less than 0.5 μV activity in a 100 ms window) and the EEG was re-referenced to the averaged mastoids (electrode 57 and 100)."

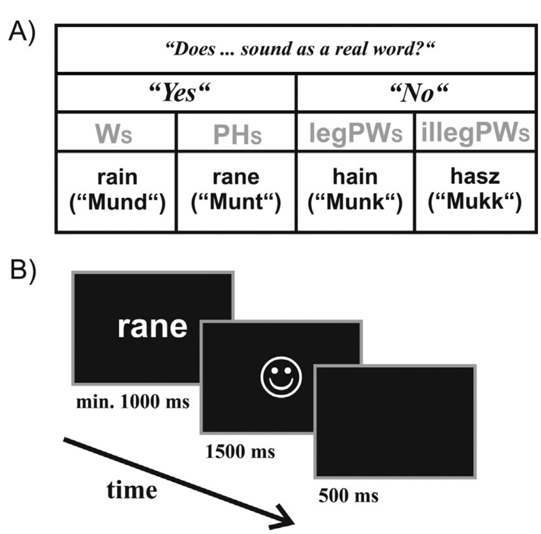

Fig. 1. The phonological lexical decision task experiment. (A) Experimental conditions and examples of the presented stimuli (German example in brackets) in each condition. (B) An example trial of the experiment. Participants were instructed to decide via button-press whether the presented word-like stimulus sounds as a real word and received immediate feedback.

Afterwards, the continuous data were segmented into epochs from −200 ms to 1200 ms relative to stimulus onset. The 200 ms long pre-stimulus interval served for baseline correction. At last, individual segments were averaged separately for each experimental condition and each group. Participants had to have a minimum of 20 artifact-free trials in each experimental condition in order to be included in the analyses. The average number of accepted trials for Ws, PHs, legPWs and illegPWs (M [SD] by a max. of 80 items), respectively was 76.46 [2.98], 77.12 [2.63], 76.90 [2.71] and 77.43 [2.46] for the TD group, 76.55 [2.50], 76.89 [2.27], 76.71 [2.18] and 77.26 [2.25] for cRSD group, 76.00 [3.87], 76.63 [3.81], 76.30 [3.42] and 76.65 [3.88] for the iRD group, and 76.08 [2.78], 76.15 [2.94], 76.72 [2.30] and 77.16 [2.87] for the iSD group. There was no significant difference between the groups in the number of accepted trials (all *ps* > .65).

Based on previous ERP studies, we expected to observe the N170 over bilateral occipito-temporal sites (e.g. Bentin et al., 1999), and the N400 over centro-parietal sites (Kutas and Federmeier, 2011). The LPC is commonly observed over left centro-parietal regions (e.g. Van Strien et al., 2009). The visual inspection of the data confirmed these assumptions. Thus, we defined our region of interests (ROIs) over three different sites: We defined a (1) bilateral occipito-temporal ROI including the electrodes 58, 59, 64, 65, 66, 69 and 70 on the left side and the electrodes 83, 84, 89, 90, 91, 95 and 96 on the right side for the N170, a (2) centro-parietal ROI including the electrodes 31, 54, 55, 61, 62, 78, 79, 80 and 129 (Cz, REF) for the N400 and a (3) left lateralized centro-parietal region including the electrodes 52, 53, 54, 60, 61, 66 and 67 for the LPC.

To determine the N170 and the N400 we searched for the most negative peak (local maxima) in the time window between 130 and 280 ms and between 300 and 450 ms, respectively. Mean peak amplitudes (including ±10 data points) and latencies were exported for each electrode of the above defined occipito-temporal and centro-parietal ROIs. For the LPC, we exported the mean amplitude value for each electrode of the left centro-parietal ROI in 4 time windows defined between 600 and 1100 ms (600–726 ms, 726–850 ms, 850–976 ms and 976–1100 ms). Dividing the component in 4 equal time windows can give insights in temporal processing differences between the groups in this late component. Differences between the conditions might emerge later in the reading impaired groups, compared to children without reading difficulties. After the above defined exportations, the values of individual peak amplitudes, latencies and mean amplitude values were averaged over the electrodes included in the respective ROI.

In order to examine whether there are differences between correctly and incorrectly spelled words within the group of children with spelling disorders (cRSD and iSD), we averaged separately for correctly and incorrectly spelled words in the W and PH conditions. TD children and children with iRD did not have enough misspellings, thus analyzes were carried out only for children with spelling disorders. Even though spelling could be assessed only for words but not for pseudohomophones, we assumed that the knowledge about the right spelling of a word implies that PHs are recognized as misspellings. Again, only participants with a minimum of 20 artifact-free trials in each condition were included in the analysis. This resulted in a sample size of N = 33 (24 children with cRSD and 9 children with iSD).[2] The average number of accepted trials (M [SD]) was 46.23 [6.76] for Ws – spelled correctly, 29.92 [6.74] for Ws – spelled incorrectly, 46.62 [6.76] for PHs – corresponding to related Ws spelled correctly, and 29.86 [6.81], for PHs – corresponding to related Ws spelled incorrectly, respectively. The averaged ERPs were processed in the same manner as described above.

2.5. Statistical analysis

Before the statistical analysis of the behavioral data, reaction times (RTs) were outlier-corrected in a two-step procedure. First, extreme values below 200 ms and above 15.000 ms were deleted. In a second step, RTs deviating more than 3 SDs from the individual mean of each subject in each condition were excluded. Based on this outlier correction 2.06% of the trials were removed. Furthermore, we only included children in the analysis with a general performance above 60% correct trials. This criterion resulted in the exclusion of three participants (see also participant section). Only trials with correct answers were included in the RT analysis. For the ERP analysis, all artifact-free segments were included.

As there were significant differences between the groups in their overall performance, which can influence interaction effects (i.e., overadditivity effect), we used z-score transformations to examine the interaction between group and condition (as proposed by Faust et al., 1999). Z-scores were obtained by subtracting each individual's overall mean (for the same answer, e.g. "yes" or "no"-answer trials) from the individual's condition mean (individual's mean of the W, PH, legPW or illegPW condition). This value was then divided by the individual's standard deviation in the respective condition. Thus, the z-score indicates a subject's performance in a given condition relative to all other same answer conditions.

For the statistical analysis of RTs, accuracy rates and the N400, we computed 2 (*condition*) × 4 (*group*) repeated measures ANOVAs, separately for the W-PH and the legPW-illegPW comparisons. The ANOVAs included the within-subject factor *condition* (W vs. PH and legPW vs. illegPW, respectively) and the between-subject factor *group* (TD group, cRSD group, iRD group vs. iSD group). For the analysis of the N170, we computed 2 (*laterality*) × 2 (*condition*) × 4 (*group*) repeated measures ANOVAs, with the additional within-subject factor *laterality* (left vs. right hemisphere), separately for the W-PH and the legPW-illegPW comparisons. For the W-PH comparison of the LPC, we computed a 4 (*time window*) × 2 (*condition*) × 4 (*group*) repeated measures ANOVA. As pseudowords are not expected to enlarge the LPC component, the LPCs of legPWs and illegPWs were not analyzed. However, orthographic knowledge might have an impact on this component, thus, we computed a 4 (*time window*) × 2 (*condition*: W vs. PH) repeated measures ANOVA separately for correctly and incorrectly spelled words in children with spelling disorder.

[2] Please note that for this analysis we did not differentiate between isolated and combined spelling disorders because of the small sample size of the eligible children with isolated spelling disorder.

The alpha level was always set at 0.05. When sphericity was violated, the degrees of freedom were corrected using Greenhouse-Geisser's procedure. Significant interactions involving the factor group were examined with two-sided post hoc *t*-tests.

3. Results

3.1. Behavioral data

3.1.1. Accuracy rates

3.1.1.1. Lexical orthographic sensitivity – W-PH comparison. We found a main effect of group ($F_{(3,\ 107)} = 6.22$, $p < .01$; $\eta_p^2 = 0.15$) and condition ($F_{(1,\ 107)} = 220.62$, $p < .001$; $\eta_p^2 = 0.67$), but no significant interaction ($p = .14$). Accuracy rates were generally high. Between samples *t*-tests revealed that the cRSD (90.19% correct; $p < .001$) and iSD (92.35% correct; $p = .05$) groups showed significantly lower accuracy rates than the TD group (94.84% correct). There was no difference between the TD and the iRD (93.69% correct) group ($p = .36$) and between the cRSD and iSD group ($p = .10$) in their accuracy rates (see Fig. 2). Accuracy rates were higher in the W- (96.24% correct) than in the PH- (89.30% correct) condition ($p < .001$).

3.1.1.2. Sublexical orthographic sensitivity – legPW-illegPW comparison. We found a main effect of group ($F_{(3,\ 107)} = 9.45$, $p < .001$; $\eta_p^2 = 0.21$) and condition ($F_{(1,\ 107)} = 40.99$, $p < .001$; $\eta_p^2 = 0.28$), and a significant interaction ($F_{(3,\ 107)} = 3.11$, $p < .05$; $\eta_p^2 = 0.08$). Follow-up t-tests revealed that the TD group (96.09% correct) had significantly higher accuracy rates than the cRSD (88.86% correct), iRD (91.37% correct) and iSD groups (89.91% correct; all *ps* < .01). There was no difference between the accuracy rates of the three deficit groups (all *ps* > .13; see Fig. 2). In line with expectations, illegal pseudowords were easier to dismiss as words (93.53% correct) than legal pseudowords (89.59% correct; $p < .001$).

The significant interaction effect was based on the smaller, non-significant difference between legPWs and illegalPWs in the TD group ($p = .062$) compared to the significant difference between the conditions in the cRSD ($p < .001$), iRD ($p < .05$) and iSD groups ($p < .01$). The mean difference (illegPW minus legPW; M [SD]) between conditions was 1.03 [3.20] for the TD group, 4.12 [5.36] for the cRSD group, 2.86 [5.07] for the iRD group and 4.62 [6.79] for the iSD group (see Fig. 2). However, as accuracy was very high in the TD group, the non-significant condition difference might be due to a ceiling effect in this group.

3.1.2. Reaction times

3.1.2.1. Lexical orthographic sensitivity – W-PH comparison. We found both a main effect of group ($F_{(3,\ 107)} = 20.84$, $p < .001$; $\eta_p^2 = 0.37$) and condition ($F_{(1,\ 107)} = 377.74$, $p < .001$; $\eta_p^2 = 0.78$), but no significant interaction ($p > .13$). Follow-up tests showed that reaction times were fastest in the TD group (1511 ms) and the iSD group (1499 ms), followed by the iRD (2045 ms) and the cRSD group (2470 ms; all *ps* < .01). There was no difference between the TD and iSD group in their RTs ($p = .94$). The condition effect indicated that RTs were faster for Ws (1632 ms) than for PHs (2130 ms; see Fig. 2).

In order to account for the possible over-additivity effect resulting from significant group differences in RTs, we analyzed the RTs using standardized z-scores. Z-score analysis revealed a significant interaction between group and condition ($F_{(3,\ 107)} = 8.45$, $p < .001$; $\eta_p^2 = 0.19$). Paired samples t-tests showed that there was a significant difference between the z-scores of Ws and PHs in all four groups (all *ps* < .001). However, comparing the difference score (PHs minus Ws) in the four groups revealed that this difference was smaller in the cRSD group than in the other three groups (all *ps* < .05), which did not differ from each other (all *ps* > .07; see Fig. 2).

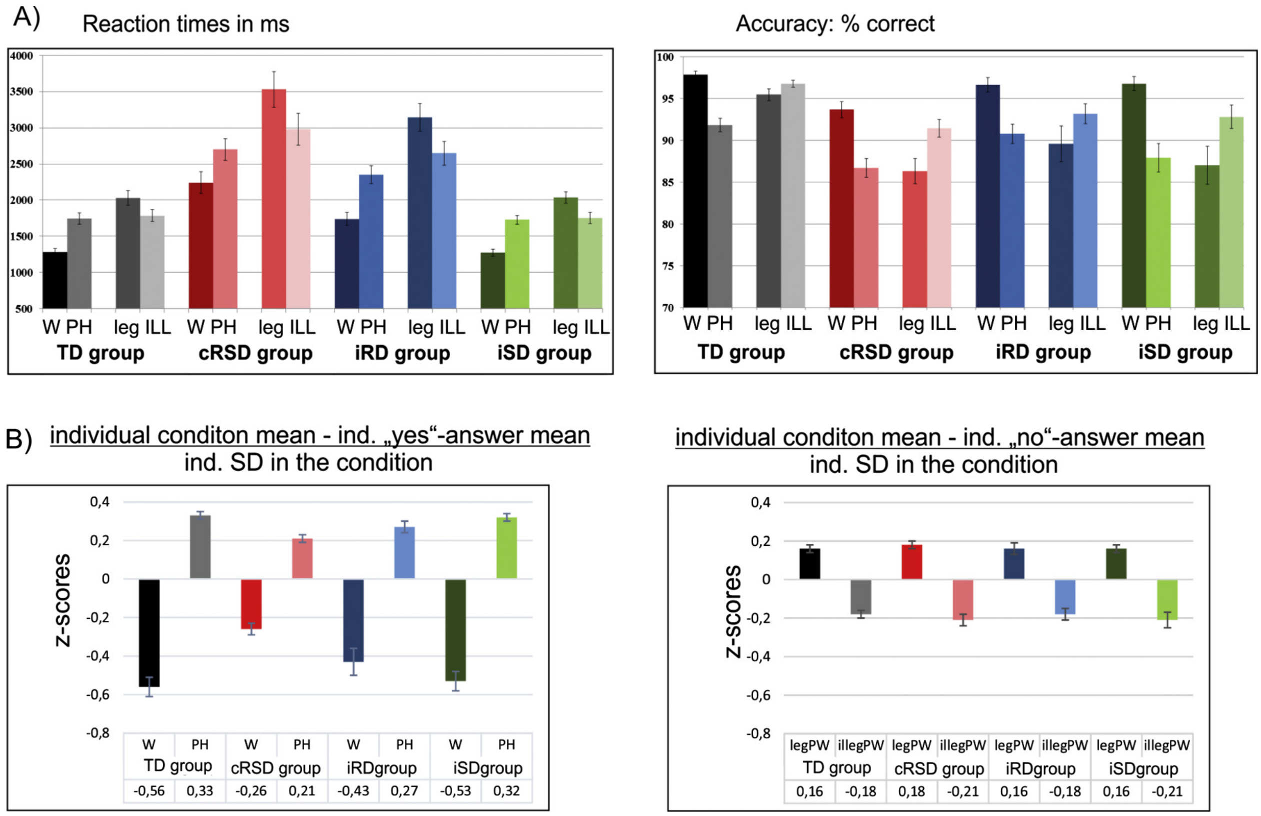

Fig. 2. Accuracy rate and reaction time results. (A) Mean values depicted separately for each condition and group for the W-PH and legPW-illegPW comparisons. Error bars represent the standard error of mean. (B) Z-values depicted separately for each condition and group with respect to the baseline of "yes"- and "no"-answer RTs.

3.1.2.2. Sublexical orthographic sensitivity – legPW-illegPW comparison. We found a main effect of group ($F_{(3,107)}$ = 18.83, p < .001; η_p^2 = 0.35) and condition ($F_{(1,\ 107)}$ = 109.74, p < .001; η_p^2 = 0.51), and a significant interaction ($F_{(3,107)}$ = 4.76, p < .01; η_p^2 = 0.12). However, the analysis of the z-scores did not confirm the interaction (p = .87, see Fig. 2), thus, the interaction reported above can most probably be accounted for by the main effect of group. Follow-up t-tests revealed that reaction times were faster in the TD group (1908 ms) and in the iSD group (1894 ms) than in the cRSD (3255 ms) and the iRD group (2896 ms; both ps < .001). There was no difference between the cRSD and iRD group (p = .14) and between the TD and iSD group in their reaction times (p = .96, see Fig. 2). Illegal pseudowords were dismissed faster (2291.57 ms) than legal pseudowords (2684.82 ms) (p < .001).

3.2. ERP data

3.2.1. Lexical orthographic sensitivity – W-PH comparison

Grand averages including the N170, N400 and LPC components of the W-PH comparison are depicted in Fig. 3. Group means of amplitudes and latencies are reported in Supplementary Material 1.

3.2.1.1. N170 amplitudes and latencies. We found a main effect of group ($F_{(3,\ 107)}$ = 3.01, p < .05; η_p^2 = 0.08) and laterality ($F_{(1,\ 107)}$ = 13.44, p < .001; η_p^2 = 0.11), but no other significant effects or interactions (all ps > .15).[3] T-tests revealed that N170 amplitudes were higher in the TD group compared to the three affected groups (all ps < .05), which did not differ from each other (all ps > .50). Amplitudes were higher in the left (−1.89 μV) compared to the right hemisphere (−0.68 μV).

With respect to N170 latencies, there was a main effect of condition ($F_{(1,\ 107)}$ = 5.42, p < .05; η_p^2 = 0.05) but no other significant effects or interactions (all ps > .07). Latencies were longer for PHs (201.64 ms) compared to Ws (198.67 ms).

3.2.1.2. N400 amplitudes and latencies. There were no significant main effects or interactions with respect to N400 amplitudes and latencies (all ps > .23).

3.2.1.3. LPC mean amplitudes. We found a significant main effect of time window ($F_{(1.44,\ 154.35)}$ = 15.00, p < .001; η_p^2 = 0.12) and condition ($F_{(1,\ 107)}$ = 26.67, p < .001; η_p^2 = 0.20) which was modified by a significant three-way interaction between time window, condition and group ($F_{(5.23,\ 186.63)}$ = 3.05, p < .05; η_p^2 = 0.06).

In order to solve the three-way interaction, we compared the conditions separately in the groups in each time window by paired samples t-tests. For the TD group, the difference between the conditions (W higher than PH) was significant in the first three time windows (spanning altogether from 600 until 976 ms; all ps < .01), but not in the fourth time window (p = .48). For the cRSD group, the difference between the conditions (W higher than PH) was only significant in the third and fourth time windows (spanning altogether from 850 until 1100 ms; both ps < .05), but not in the first and second time window (both ps > .08). For the iRD group, the difference between the conditions (W higher than PH) was significant in the first three time windows (all ps < .05), and approached significance in the fourth time window (p = .05). For the iSD group, the difference between the conditions was only significant in the first and second time windows (spanning

[3] Also the analysis of the vertex positive potential (VPP; the positive counterpart of the N170; e.g. Rossion et al., 2003) over a frontocentral ROI (including the electrodes 4, 5, 6, 11, 12, 16 and 19) did not reveal significant effects or interactions related to condition differences (all ps > .13).

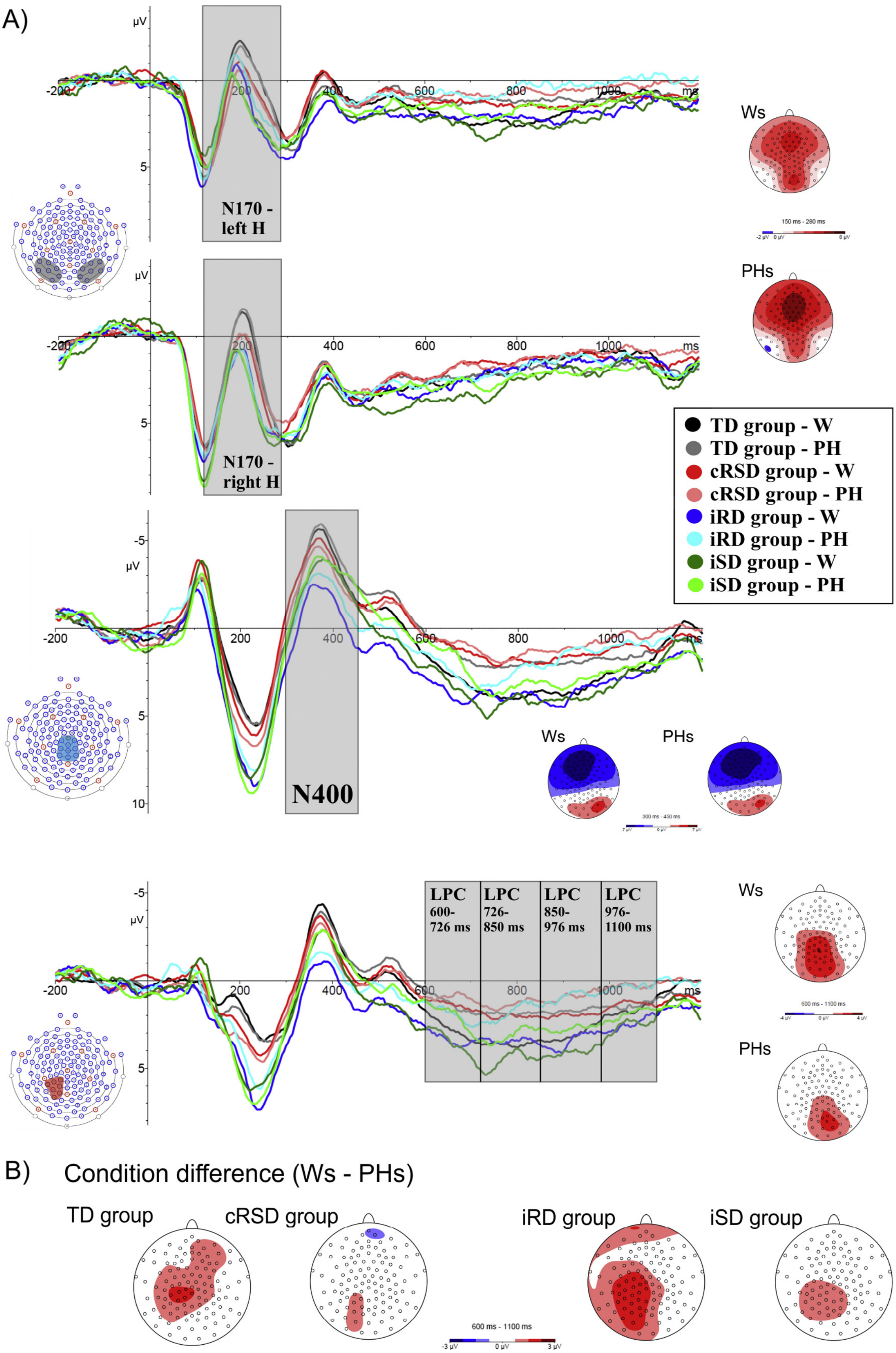

Fig. 3. Illustration of the grand average ERPs of the W-PH comparison. (A) ERPs depicted separately for the left and right occipito-temporal (N170), centro-parietal (N400) and left centro-parietal (LPC) ROIs and different groups. Topographic maps on the right side demonstrate the overall activation pattern in the time window of the components; N170 - 130–280 ms, N400: 300–450 ms, LPC: 600–726 ms, 726–850 ms, 850–976 ms and 976–1100 ms. Negativity is depicted upwards. (B) Topographic distribution of the LPC condition effect (Ws - PHs) in the time window between 600 and 1100 ms.

altogether from 600 until 850 ms; both $ps < .05$), but not in the third and fourth time windows (both $ps > .10$; see Supplementary Material 1 and Fig. 3).

3.2.1.4. Effect of orthographic knowledge on the LPC mean amplitudes in the two spelling disorder groups (cRSD and iSD). In order to examine how word-specific orthographic knowledge for the tested items affects LPC amplitudes, the W-PH comparison was calculated separately for correctly and incorrectly spelled words in the two groups with spelling disorders (cRSD and iSD). Grand averages of the LPC amplitudes are depicted in Fig. 4, and mean amplitudes and standard deviations are reported in Supplementary Material 2.

3.2.1.4.1. Correctly spelled words. We found a main effect of condition ($F_{(1,\ 32)} = 4.95$, $p < .05$; $\eta^2_p = 0.14$), but no other significant effect or interaction (both $ps > .08$). Amplitudes were higher for Ws (2.99 µV) compared to PHs (1.77 µV).

3.2.1.4.2. Incorrectly spelled words. In contrast to correctly spelled words, there was no condition effect for incorrectly spelled words, indicating that Ws and PHs elicited comparable amplitudes. We found a main effect of time window ($F_{(2.08,\ 66.51)} = 4.24$, $p < .05$; $\eta^2_p = 0.12$), but no other significant effect or interaction (both $ps > .40$). Follow-up tests showed that LPC mean amplitudes were higher in the second (1.85 µV) and third time windows (1.81 µV; all $ps < .05$) than in the first (1.11 µV) and fourth time windows (1.14 µV).

3.2.2. Sublexical orthographic sensitivity – legPW-illegPW comparison

Grand averages including the N170 and N400 components of the legPW-illegPW comparison are depicted in Fig. 5. Group means of amplitudes and latencies are reported in Supplementary Material 3.

3.2.2.1. N170 amplitudes and latencies

For the N170 amplitudes, we found a main effect of laterality ($F_{(1,\ 107)} = 9.43$, $p < .01$; $\eta^2_p = 0.08$), indicating that amplitudes were higher in the left (−1.80 µV) compared to the right hemisphere (−0.79 µV). The threefold interaction between laterality, condition and group approached significance ($F_{(3,\ 107)} = 3.16$, $p = .05$; $\eta^2_p = 0.07$).

In order to solve the threefold interaction, conditions were compared separately for each group and in each hemisphere by paired samples t-tests. For the TD group, the difference between the conditions was marginal significant in the right hemisphere ($p = .06$; illegPW higher than legPW), but not in the left hemisphere ($p = .91$). For the cRSD, iRD and iSD groups, the difference between the conditions was never significant (all $ps > .30$).

With respect to N170 latencies, there was a main effect of condition ($F_{(1,\ 107)} = 6.93$, $p < .05$; $\eta^2_p = 0.06$) but no other significant effects or interactions (all $ps > .09$). Latencies were longer in the legPW (201.84 ms) compared to the illegPW (199.26 ms) condition.

3.2.2.2. N400 amplitudes and latencies

There were no significant main effects or interactions with respect to N400 amplitudes and latencies (all $ps > .17$).

4. Discussion

The aim of the present study was to investigate group differences in lexical and sublexical orthographic processing between TD children and children with combined and with isolated reading and/or spelling disorder. For this reason, we implemented a PLD-task with four types of stimuli: Ws (real words), PHs (pseudohomophones derived from Ws), legPWs (pseudowords following German orthography) and illegPWs (pseudowords including sublexical orthographic elements violating German orthography) while recording ERPs.

The comparison of high-frequency Ws and corresponding PHs reflects lexical orthographic processes, whereas the comparison of legPWs and illegPWs reflects sublexical orthographic sensitivity. The results of the two comparisons are discussed separately below.

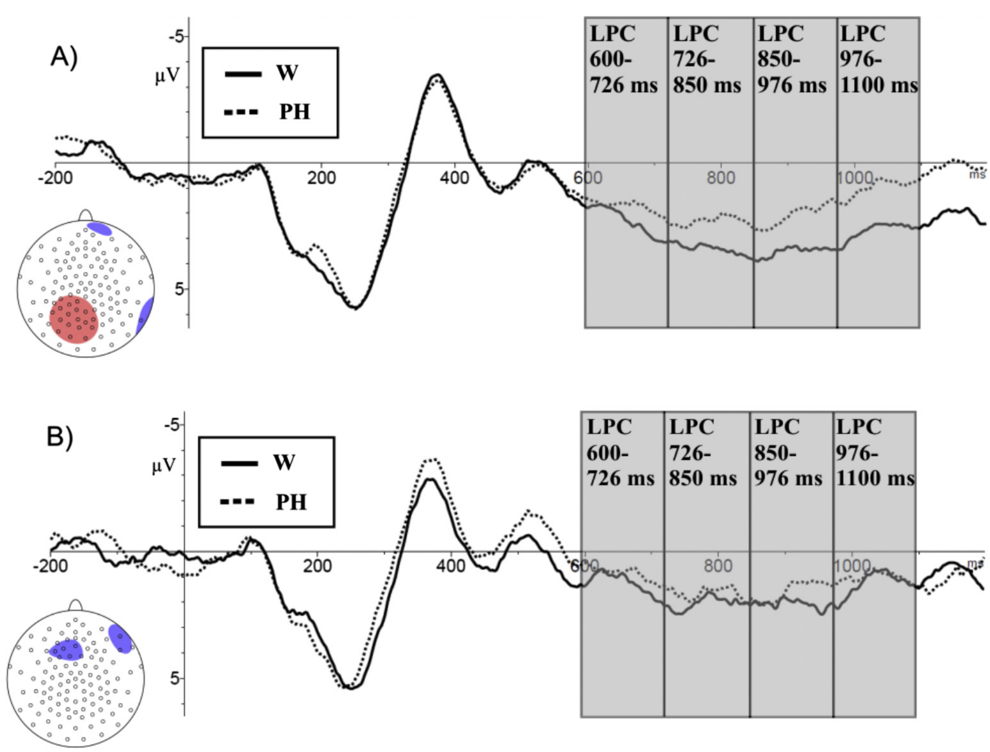

Fig. 4. Illustration of the LPC amplitudes of the W-PH comparison in the spelling disorders group depicted separately for (A) correctly and (B) incorrectly spelled words. The different time windows (600–726 ms, 726–850 ms, 850–976 ms, 976–1100 ms) are highlighted in grey. Negativity is depicted upwards.

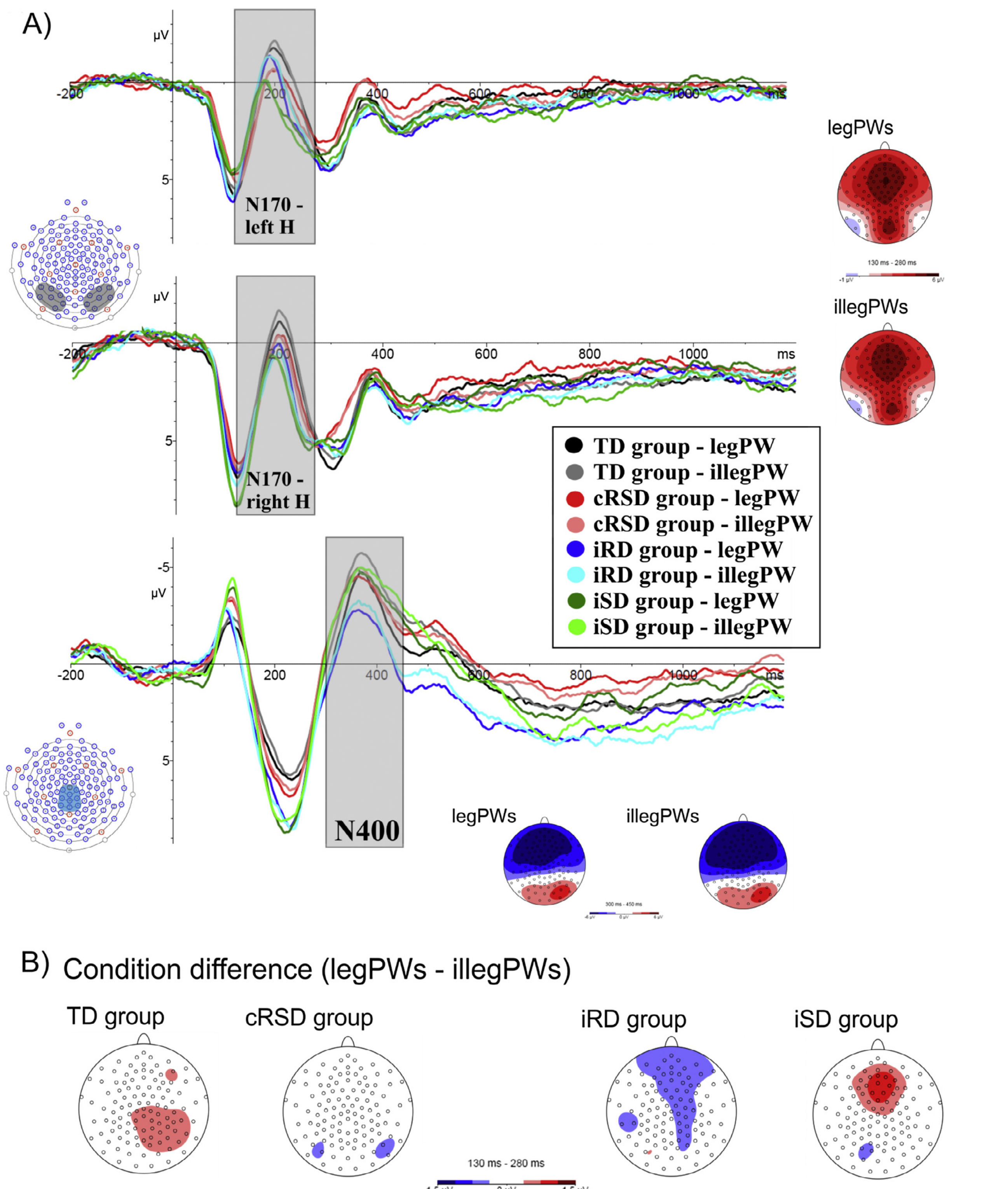

Fig. 5. Illustration of the grand average ERPs of the legPW-illegPW comparison. (A) ERPs depicted separately for the left and right occipito-temporal (N170) and centro-parietal (N400) ROIs and different groups. Topographic maps on the right side demonstrate the overall activation pattern in the time window of the components; N170 - 130–280 ms, N400: 300–450 ms. Negativity is depicted upwards. (B) Topographic distribution of the N170 condition effect (legPWs - illegPWs) in the time window between 130 and 280 ms.

4.1. Lexical orthographic processing – W-PH comparison

On the behavioral level, we found higher accuracy rates and shorter RTs for Ws compared to PHs in all groups, indicating that lexical knowledge might be used even in poor readers and poor spellers – at least for some of the words used in the experiment.

Although all groups showed an advantage for Ws over PHs, group differences still emerged: children in the TD and iRD groups were more accurate than children in the two spelling impaired groups (cRSD and iSD), possibly reflecting poorer orthographic representations in the spelling impaired groups. However, it should be noted that accuracy rates were generally high across all groups, ranging between 90 and 95% correct.

With respect to group differences in response times (RTs), we found shorter RTs for both conditions in the TD and iSD groups compared to the two reading impaired groups (cRSD and iRD). Longer RTs during the PLD-task in the two reading impaired groups are likely to result from longer reading times in these groups.

The condition difference in the RTs was mirrored in the ERP latency results: N170 latencies were shorter for Ws than for PHs in all groups. Most probably, orthographic familiarity of the high frequent Ws has facilitated the first step of visual processing of the word stimuli. However, there was no difference in the N170 amplitude heights of Ws compared to PHs. N170 amplitudes are commonly interpreted in the context of print sensitivity, with higher amplitudes for printed (pseudo-) words in contrast to false fonts (for a review see Maurer and McCandliss, 2008). Thus, differences in N170 amplitude heights between word-like conditions, such as Ws vs. PHs, were not necessarily expected in our study. In line with previous studies (Hasko et al., 2013; Bentin et al., 1999), this finding implies that lexical orthographic familiarity (contrast between Ws and PHs) does not affect N170 amplitude heights. However, lexical orthographic familiarity accelerates visual processing of printed material, and leads to shorter N170 latencies.

With respect to group differences in the N170, we found generally higher amplitudes in the TD group, compared to the cRSD, iRD and iSD groups. This group difference in the N170 amplitudes might reflect the higher familiarity of skilled readers (our TD group) with visual word-like stimuli. The perceptual expertise framework for evaluating N170 effects implies larger N170 amplitudes for a specific stimulus category, for which a perceptual expertise exists, e.g. N170 amplitudes are increased in bird-experts looking at birds, and in car-experts looking at cars (for an overview see Maurer and McCandliss, 2008). Thus, our finding of higher N170 amplitudes in the TD group compared to children with reading and/or spelling deficits can be interpreted as higher perceptual expertise with word-like stimuli in TD children compared to children with cRSD, iRD or iSD. This is in line with findings of Hasko et al. (2013), who reported higher print sensitivity in TD 8-year-olds compared to age-matched children with dyslexia when comparing the difference waveform built between non-linguistic false fonts and linguistic material. The difference waveform was higher in TD children than in children with dyslexia.

In sum, it can be concluded that the reader's expertise (high vs. low reading expertise) influences N170 amplitude heights of both Ws and PHs in PLD tasks. In contrast, lexical orthographic familiarity of the word material affected N170 latencies but did not modulate N170 amplitude heights.

With respect to the LPC, we found higher mean amplitudes for Ws compared to PHs in the group of TD and iRD children, which is in line with our expectations. This component is commonly interpreted in the context of word recognition (e.g., enlarged for old/learned words in contrast to new words) and orthographic lexical access (Balass et al., 2010; Rugg and Curran, 2007). Thus, children with iRD seem to have intact orthographic representations comparable to TD children, which is in line with their age-appropriate spelling skills. However, there was a critical difference between TD and iRD children in the temporal sequence of the LPC. The difference between the word conditions emerged after 600 ms in both groups, but while it was finished after 976 ms in the TD group, the difference between the conditions lasted longer in the iRD group (at least until 1100 ms). The finding that both groups show a clear difference between Ws and PHs indicates that they use their word-specific lexical representations during task performance. However, the temporal difference observed between the TD group and the iRD group shows that lexical processing was completed earlier in TD children, and thus, was probably more efficient.

This novel finding contributes to our understanding of the reading fluency deficit in poor readers. The finding suggests that deficits in reading fluency can occur even if word-specific knowledge is intact, as it is the case for children with iRD. Furthermore, our ERP results provide a first evidence that slow reading in this group might be caused by less efficient and prolonged lexical processing rather than by deficits in built-up lexical orthographic representations.

For the two spelling disabled groups (cRSD and iSD), the difference between the mean LPC amplitudes for Ws and PHs was smaller and less stable, appearing only in two out of four time windows. The smaller difference between Ws and PHs in the two spelling disabled groups compared to good spellers is likely to reflect poorer orthographic knowledge in these children. However, given that the word material was relatively easy, even poor spellers have probably built-up word-specific orthographic representations for at least some of the presented words which would explain the inconsistent W-PH difference observed in the two groups of poor spellers. In order to investigate the influence of word-specific knowledge on LPC amplitudes more directly on an individual level, we re-analyzed the LPC amplitudes in poor spellers separately for correctly and incorrectly spelled words.

For correctly spelled words, mean LPC amplitudes were higher for Ws than for PHs, indicating lexical processing of these words. However, there was no difference between the conditions with respect to incorrectly spelled words. We suggest that children with spelling deficits might have intact orthographic representations for some easy words, for which word-specific knowledge is available. For these words, they might rely on lexical reading processes. However, for the substantial number of incorrectly spelled words, where orthographic representations were incomplete or missing, poor spellers needed to use alternative reading strategies (e.g. partial cue reading or sublexical decoding). Accessing incomplete word representations or using a compensatory decoding strategy would likely reduce the difference between Ws and PHs, because the same strategy is used for both word types. In sum, our results indicate that children with spelling disorder might adapt their reading strategies depending on their word specific knowledge. This result also highlights the importance of assessing orthographic knowledge of the experimental word material used in dyslexia research, in order to differentiate between word-specific items that are stored and those that are not available in orthographic memory.

Lastly, we would like to discuss the fact that we did not find any group differences in N400 amplitudes, which contradicts the results reported by Hasko et al. (2013, 2014). This contradiction might be explained by the age difference between our sample and the participants of Hasko et al. (2013, 2014). Although, to our knowledge, there is no developmental study which has directly compared the N400 in dyslexic second- and third-graders, we can make some assumptions concerning the development of these effects based on the findings reported by Silva-Pereyra et al. (2003) and Coch and Holcomb (2003). While Silva-Pereyra et al. (2003) did not find any group difference between poor readers and TD 10-year-old children in a categorization task, Coch and Holcomb (2003) reported a "somewhat curious lack" of N400 amplitudes in younger children aged 7-years old with low reading ability compared to high-ability readers. The dyslexic group of Hasko et al.'s (2013, 2014) sample (8-year-olds) might be more comparable to the low-ability beginning readers of Coch and Holcomb (2003) whereas our participants (9–10-year-olds) might be closer related to the older participants of Silva-Pereyra et al. (2003). This interpretation is further supported by findings showing that semantic effects on the N400 (difference between words and pseudowords) do not seem to change after third grade (Coch, 2015). However, as there are studies which have found abnormal N400 activation even in older dyslexic individuals (e.g. Rüsseler et al., 2007; Johannes et al., 1995), the question whether N400 amplitudes are affected in dyslexia still has to be determined. Studies examining different age groups within one experimental paradigm might be a good way to clarify this issue. Based on our findings, we suggest that semantic processing of Ws and PHs are comparable in TD 9-year-old children and children with reading and/or spelling disorders.

Taken together, the results of the W-PH comparison indicate that TD children show a higher sensitivity for word-like material than reading and/or spelling impaired children. This sensitivity was already evident within the first 170 ms after stimulus presentation.

Furthermore, the current ERP results support behavioral findings suggesting that children with iRD have intact orthographic representations which are comparable to TD children and which are used for both reading and spelling. The difference between TD and iRD children lies most probably in the efficiency of lexical processes. Our findings support the idea that slow reading speed results from less effective lexical access (Moll and Landerl, 2009; Wimmer and Mayringer, 2002). Given that the spelling process is comparably slow, slow access of lexical representations is not a problem for spelling; however, slow access of lexical representations clearly affects reading fluency.

Children with spelling deficits have missing or incomplete orthographic representations for a large number of words. For easy, correctly spelled words, our ERP findings suggest that poor spellers use their intact lexical representations for reading, resulting in higher amplitudes for Ws than for PHs, comparable to TD children. For incorrectly spelled words, the differences between Ws and PHs were diminished, suggesting that when representations are incomplete or missing, different reading strategies are used.

4.2. Sublexical orthographic sensitivity – legPW-illegPW comparison

We found shorter RTs and higher accuracy rates for illegPWs compared to legPWs. As expected, pseudowords containing illegal sublexical elements were rejected faster and with higher accuracy rates than legal pseudowords. These findings were also reflected in the N170 latencies: N170 latencies were shorter for illegPWs compared to legPWs.

When comparing the groups, we found shorter RTs in the TD and iSD groups than in the two reading impaired groups (cRSD and iRD). In line with the results from the W-PH comparison, shorter RTs in the TD and iSD groups compared to the cRSD and iRD groups are likely to reflect reduced reading speed in the two reading impaired groups.

With respect to accuracy rates, we found higher overall accuracy rates and a smaller difference in accuracy rates between illegPWs and legPWs in the TD group compared to all three deficit groups (cRSD, iRD and iSD). Higher accuracy rates and smaller condition effects in the TD group compared to the other three groups might be related to more intense reading experience in the TD group. TD children identified pseudowords with high accuracy, regardless of whether they contained illegal sublexical word patterns or not. Given that accuracy rates were at ceiling in this group, there was probably no room for improvement by the condition manipulation. In contrast, children with reading and/or spelling disorder were less accurate in identifying pseudowords. These groups benefited from illegal letter patterns, which facilitated the identification of the pseudoword.

With respect to the N170, we found higher amplitudes to illegPWs compared to legPWs within the TD group. This difference was evident only in the right hemisphere, which is in line with findings showing a tendency towards right hemispheric processing of non-orthographic material (Bentin et al., 1999; Maurer and McCandliss, 2008). Thus, TD children might have detected relatively early that illegPWs are not part of the normal German orthography, and processed them as non-orthographic stimuli.

However, the conclusion that the N170 amplitude difference between legPWs and illegPWs reflects sensitivity for the violation of German orthography must be treated with caution, given that it is not possible to control for differences in the trigram and bigram frequencies of the legPWs and illegPWs. Thus, the effects of sublexical orthographic sensitivity cannot be clearly separated from the effects of simple visual familiarity (frequency effects).

Importantly, there was no difference between the N170 amplitudes of legPWs and illegPWs in the other three groups. Thus, reading and/or spelling impaired children were relatively insensitive of the irregularity of illegPWs. For the spelling disorder groups, insensitivity is likely to reflect poor orthographic sensitivity at a sublexical level. For the iRD group, missing condition effects might either be a consequence of their slowed-down visual-verbal access or a result of their deficient reading experience. As children with iRD read probably less than TD children, they might not have developed sublexical orthographic sensitivity at the same level as TD children. However, as this is the first study to examine neurophysiological correlates of children with iRD, further studies are needed to replicate these findings.

With respect to the N400, we did not find any group differences, which is in contrast to the findings of Hasko et al. (2013, 2014). The possible reason for this discrepancy might be found in the age difference between the study samples, as already discussed above.

Taken together, TD 9-year-old children showed neurophysiological sensitivity for the violation of German orthographic rules in a very early time window, while children with reading and/or spelling deficits were relatively insensitive to these irregularities, at least in this very early time window of the neurophysiological measurement. However, all groups benefited from the illegal characters of the illegPWs on the behavioral level, thus children with reading and/or spelling disorders have also noted the irregularities, but not in the same fast and automatic way as TD children. We assume that children with reading and/or spelling problems detect illegal letter-combinations in a later processing stage, leading to an earlier termination of the pseudoword-reading process for illegPW and thus to shorter RTs for illegPWs compared to legPWs.

4.3. Limitations

We examined a very homogenous sample, consisting of mostly nine- and ten-year-old children (age range: 8.4–11.3 years) with the same amount of schooling. Although a homogenous sample increases the power of statistical tests, it reduces the generalizability of the results. Thus, future studies need to assess whether the current findings can be transferred to other age groups.

Furthermore, it must be considered that our participants were all German-speaking. German is characterized as a shallow, consistent orthography, although it is less consistent in the spelling than in the reading direction. However, it is possible that some of the correct word spellings have been guessed without having the correct orthographic representation stored in long term memory. This possibility was not considered in the analysis of correctly and incorrectly spelled words. Future studies should consider to evaluate not only the spelling of the word material, but also to gather confidence ratings of the spellings.

The word material used was relatively simple in order to have enough correctly spelled words within the iSD and cRSD groups for our analysis. However, the inclusion of more difficult words might be helpful to get a more realistic picture of the reading difficulties of children with iRD and to be able to examine the neurophysiological correlates of correctly and incorrectly spelled words in all four groups.

4.4. Conclusions

Our study is the first to examine the neurophysiological correlates of word processing in isolated reading and spelling disorders. Our findings support the assumption that slow reading speed in iRD might be rather related to inefficient lexical access than to deficits in building-up word-specific orthographic representations. In contrast, spelling deficits seem to be attributed to deficient and partly missing orthographic representations.

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Conflict of interest

None of the authors have potential conflicts of interest to be disclosed.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.clinph.2017.12.010.

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STUDIE2:
Deficits in Letter-Speech Sound Associations but Intact Visual Conflict Processing in Dyslexia: Results from a Novel ERP-Paradigm

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Deficits in Letter-Speech Sound Associations but Intact Visual Conflict Processing in Dyslexia: Results from a Novel ERP-Paradigm

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The reading and spelling deficits characteristic of developmental dyslexia (dyslexia) have been related to problems in phonological processing and in learning associations between letters and speech-sounds. Even when children with dyslexia have learned the letters and their corresponding speech sounds, letter-speech sound associations might still be less automatized compared to children with age-adequate literacy skills. In order to examine automaticity in letter-speech sound associations and to overcome some of the disadvantages associated with the frequently used visual-auditory oddball paradigm, we developed a novel electrophysiological letter-speech sound interference paradigm. This letter-speech sound interference paradigm was applied in a group of 9-year-old children with dyslexia ($n = 36$) and a group of typically developing (TD) children of similar age ($n = 37$). Participants had to indicate whether two letters look visually the same. In the incongruent condition (e.g., the letter pair A-a) there was a conflict between the visual information and the automatically activated phonological information; although the visual appearance of the two letters is different, they are both associated with the same speech sound. This conflict resulted in slower response times (RTs) in the incongruent than in the congruent (e.g., the letter pair A-e) condition. Furthermore, in the TD control group, the conflict resulted in fast and strong event-related potential (ERP) effects reflected in less negative N1 amplitudes and more positive conflict slow potentials (cSP) in the incongruent than in the congruent condition. However, the dyslexic group did not show any conflict-related ERP effects, implying that letter-speech sound associations are less automatized in this group. Furthermore, we examined general visual conflict processing in a control visual interference task, using false fonts. The conflict in this experiment was based purely on the visual similarity of the presented objects. Visual conflict resulted in slower RTs, less negative N2 amplitudes and more positive cSP in both groups. Thus, on a general, basic level, visual conflict processing does not seem to be affected in children with dyslexia.

Keywords: dyslexia, letter-speech sound associations, visual conflict processing, ERP, N1, N2, conflict slow potential

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INTRODUCTION

The ability to read is very fundamental in our daily life, allowing the transfer of knowledge and information. It is not only important for an individual's academic and professional carrier, but is crucial for a successful integration into a modern society. Thus, difficulties in the acquisition of reading skills can have a negative impact on several aspects of life. This might be the case in developmental dyslexia (dyslexia), a developmental disorder affecting approximately 5–11% of the population (Jones et al., 2016). Children and adults with dyslexia have difficulties in accurate or fluent reading and accurate spelling, despite adequate schooling, intelligence, and intact sensory abilities (Lyon et al., 2003; for a review see Peterson and Pennington, 2012).

One of the most important prerequisites of reading in alphabetic orthographies is the build-up of letter-speech sound associations (Ehri, 2008). Longitudinal studies indicate that letter-sound knowledge is a strong predictor of later literacy skills (Lonigan et al., 2000; Schatschneider et al., 2004; Caravolas et al., 2012). Children with a familial risk for dyslexia take longer to learn the associations between letters and speech-sounds than control children (Torppa et al., 2006), and the build-up of associations might be less automatic (Bishop, 2007). Even though there are no differences between good and poor readers in their behaviorally measured letter knowledge (i.e., knowing the letter and the corresponding sound) (Stein and Walsh, 1997; Facoetti et al., 2001), neurophysiological studies suggest that automatic integration of letters and speech-sounds (i.e., immediate activation of the speech sound by the sight of a letter) might be a problem in dyslexia not only in early but even in adult years (Blomert, 2011; Froyen et al., 2011). Automated letter-speech sound associations are likely to play a crucial role for fluent reading given that fluent reading requires fast access from the visually presented letter or word to its phonological form. Thus, understanding the developmental differences in the build-up of automated letter-speech sound associations between children with dyslexia and typically developing (TD) children might help to identify and better understand the problems which may cause difficulties in reading acquisition. For this reason, we examined the strength of letter-speech sound associations in children with dyslexia and TD children in a newly developed event-related potential (ERP) paradigm.

Until now, automatization of letter-speech sound associations has been commonly examined applying a visual-auditory passive oddball paradigm during ERP measurement (Froyen et al., 2008; Moll et al., 2016). In this visual-auditory oddball paradigm, frequent standard congruent letter-sound pairs (e.g., the letter "a" with the sound /a/) are compared to rare deviant incongruent letter-sound pairs (e.g., the letter "a" with the sound /o/). The measured ERP component derived from the continuous electroencephalogram (EEG) is called audiovisual mismatch-negativity (audiovisual MMN). The audiovisual MMN is measured as a difference wave, built from the difference between the standard and deviant condition, reflecting the strength of letter-speech sound integration. Enhanced negativity in the deviant (/o/-sound) condition is caused not only by the deviation of the /o/-speech sound from the standard /a/-speech sound, but further strengthened by the dissociation between the presented /o/-speech sound and the standard letter "a" (Froyen et al., 2008, 2009, 2011; Žarić et al., 2015). However, this visual-auditory oddball paradigm has also some disadvantages (for a review see, Bishop, 2007). It is a passive paradigm, thus behavioral correlates of the neurophysiological differences cannot be assessed. This might be problematic, especially when assessing children and clinical populations. The experimental setup of the visual-auditory passive oddball paradigm requires a relatively high stimulus-repetition rate, which might lead to problems in maintaining attention in these populations. Without behavioral measurements as a control for task performance, it can be questioned whether the participants correctly processed the task. Furthermore, the audiovisual MMN component is measured as a difference waveform between the standard and deviant condition, which results in a lower signal-to-noise ratio than measuring the original ERP waveforms. It has been shown that the test-retest reliability of the audiovisual MMN is lower than the reliability of the standard peaks (e.g., P1, N1, P2) (McArthur et al., 2003). Lastly, the experimental situation of seeing the letter and hearing the speech sound at the same time does not reflect the silent reading situation experienced in everyday life, which can compromise external validity. In real life reading situations, children are only seeing the letters but not hearing the speech sounds.

Thus, we developed a new neurophysiological paradigm to measure automatization strength using the theoretical framework of the classical Stroop-paradigm (Stroop, 1935) and the letter-matching paradigm described by Posner and Mitchell (1967), which we named letter-speech sound interference paradigm. In the classical Stroop-paradigm, words for colors are presented in different colors. In the incongruent condition, the color of the word and the meaning of the word is not the same (e.g., the word red written in green), whereas in the congruent condition both the meaning and the color of the word are the same (e.g., the word red is written in red). Participants have to respond to the color of the word presented and ignore the meaning of the word. In fluent readers, response times (RTs) are typically slower in the incongruent than in the congruent condition. This effect is called the Stroop-interference effect (for a review see MacLeod, 1991). The interference effect is not present in non-readers (Schadler and Thissen, 1981), but starts to increase with the progress of reading instruction, when reading becomes more automatized and fluent (Peru et al., 2006). Thus, the Stroop-interference effect can be explained by the automatic activation of the task-irrelevant information (in this case the word meaning), which is in conflict with the task-relevant information (the color of the word) and slows RTs. The size of the interference effect is therefore an indicator of the conflict between the task-irrelevant and task-relevant information and thus reflects the degree of reading automatization.

In our letter-speech sound interference paradigm, the task of the participant is to indicate whether two letters look exactly the same, irrespective of which phoneme they represent. This idea is similar to the letter matching paradigm, first implemented by Posner and Mitchell (1967). However, until now, the letter-matching paradigm was mainly used to analyze visual recognition and memory retrieval processes. To our best knowledge, we are the first to apply the letter-matching paradigm in the context of letter-speech sound associations and within the theoretical framework of an interference effect using ERP measurements.

In analogy to the Stroop-studies, we assume that the participants in our letter-speech sound interference paradigm have two concurrent sources of information: their task is to decide whether two visually presented letters look physically the same. The task-relevant information thereby is the visual appearance of the letters (e.g., the visual characteristics of "A" or "a"), whereas the information about the associated speech-sound (e.g., the phoneme /a/), which is supposed to get automatically activated, is irrelevant. An incongruent trial in this case would be, for example, the letter-pair A-a, because the visual appearance of the letters is not the same, even though they can be assigned to the same phoneme /a/. Thus, the visual task-relevant information is in favor of a "no" (they are not the same) response, but the automatically activated phonological information suggest a "yes" (they are the same) response. In a congruent trial, like for example the letter-pair A-e, both the visual appearance and the associated speech sound of the letters are different, meaning that both the visual information and the automatically activated phonological information suggest a "no" (they are not the same) response. Letter-speech sound associations are highly automatic in advanced readers (Froyen et al., 2009), thus speech sounds associated with the letters are expected to get automatically activated resulting in an interference effect in the incongruent condition. This would lead to slower RTs in the incongruent (e.g., A-a) than in the congruent (e.g., A-e) condition. In the German orthography, where letter-speech sound correspondences are fairly consistent, this effect is expected to be especially strong.

The size of the reaction time difference and the difference between the ERP components of the incongruent and congruent conditions is expected to give us insights about letter-speech sound automatization strength. Even if there are no differences between good and poor readers in their behaviorally measured letter-sound knowledge (Froyen et al., 2011), we might be able to find group differences when we measure letter-speech sound automatization strength, rather than letter knowledge and apply more sensitive methods, like EEG, rather than only behavioral measurements.

However, since the implemented neurophysiological letter-speech sound interference paradigm is entirely new, we have no reference studies as to what ERP components to examine, but we assume that the conflict in the incongruent condition would lead to similar ERP-effects than other conflict related paradigms like the Stroop- and the flanker task. Based on this literature, we decided to focus our analysis on three classical, conflict-related ERP components. We analyze two early components, the N1 and the N2, and one late component, the conflict slow potential (cSP).

The fronto-central N1 has been shown to be sensitive to conflict in Stroop-, and flanker-task experiments applying either visual (Johnstone et al., 2009) or auditory stimuli (Näätänen and Picton, 1987; Henkin et al., 2010; Yu et al., 2015). It is commonly measured over fronto-central sites as the most negative deflection between 100 and 200 ms after stimulus presentation and has been associated with conflict detection (Yu et al., 2015). The results of auditory Stroop experiments suggest that fronto-central N1 amplitudes are less negative in incongruent than in congruent trials (Lew et al., 1997; Henkin et al., 2010; Yu et al., 2015); however, there is also a study which found the opposite pattern in a visual flanker task (Johnstone et al., 2009). Thus, the direction of the conflict-related N1 amplitude modification appears to depend on the characteristics of the applied stimuli and paradigm.

The fronto-central N2, commonly observed as a negative deflection peaking approximately 250–350 ms after stimulus onset, reflects conflict detection and conflict monitoring processes mediated by the anterior cingulate cortex (for a review see, Larson et al., 2014). Depending on the paradigm, the N2 amplitude is either more negative in incongruent than in congruent trials (van Veen and Carter, 2002a,b; Yeung et al., 2004; Johnstone et al., 2009) or more negative in congruent than in incongruent trials (Yu et al., 2015). However, there is also a study, which did not find any effects of conflict on the N2 amplitudes (Henkin et al., 2010). Thus, the existing literature is inconclusive about the occurrence and directionality of the conflict-related N2 amplitude effect.

The cSP is a sustained positivity beginning approximately 500 ms after stimulus presentation. Over centro-parietal sites, the cSP has been found to be more positive on incongruent trials than on congruent trials (Liotti et al., 2000; Larson et al., 2009; Donohue et al., 2012; Yu et al., 2015). It has been commonly interpreted as reflecting conflict resolution (West and Alain, 2000; West, 2003) or response selection processes (West et al., 2005). The neural generators of the cSP are most probably the lateral frontal and posterior cortices (West, 2003; Hanslmayr et al., 2008; for a review see Larson et al., 2014).

The effect of conflict on these three ERP might, however, be different in individuals with developmental dyslexia. Mahé et al. (2014) for example, found reversed N1 and missing N2 effects in a group of adults with dyslexia when compared to typical readers in a flanker task comprising congruent and incongruent trials. Thus, in order to ensure that the congruency-related effects of our letter-speech sound interference experiment reflect differences in letter-speech sound association strength and not only general differences in conflict processing between the groups, we implemented a control task, which we named visual interference experiment. Instead of real letters, we used false fonts, which were visually similar to the letters. The conflict in the incongruent condition of this experiment is based purely on the visual characteristics of the stimuli because there are no speech sounds associated with the false fonts. The task of the participants was to indicate whether two false fonts looked exactly the same. In the incongruent condition the same fonts were presented in different sizes, whereas in the congruent condition two different false fonts were displayed. The conflict in this visual interference experiment is thus based on the visual similarity of the stimuli, whereas the conflict in the letter-speech sound interference experiment is caused by the automatic activation of the letter-related speech sounds.

Taken together, our study comprising the letter-speech sound interference and the visual interference experiment is designed to answer the following questions:

(1) Do children with dyslexia show impairments in the automatization of letter-speech sound associations when compared to TD 9-year-olds? The difference from previous investigations of this question is the application of single letter-stimuli, without the synchronous presentation of auditory stimuli. Thus, our paradigm might be more closely related to the everyday situation of silent reading than the synchronous presentation of letters and sounds. This might increase external validity. Furthermore, the opportunity to assess individual task performance might help to control for motivational and attentional problems and to increase the reliability of the measurement.
(2) Is the time point of speech-sound activations by the sight of letters delayed in dyslexia? The combination of our paradigm with the high temporal resolution of ERP-measurements can help us to answer the question, at which time point speech sounds associated with letters get activated. This information could help us to shed more light on the causes of dysfluent reading in dyslexia.
(3) Are conflict-processing difficulties in dyslexia limited to specific, language-related domains, or do they extend in other domains? Dyslexia-related conflict processing literature is very sparse. At the moment, the only ERP-study examining conflict processing in dyslexia is the study of Mahé et al. (2014). However, their study implemented a type of flanker task, which examines a special aspect of visual conflict control, focusing on the suppression of flankers. Visual processing deficits may not be as strongly related to the core symptoms of dyslexia as language-related deficits, thus it might be difficult to relate the findings in this domain to the specific reading difficulties in dyslexia. Our letter-speech sound interference experiment extends the dyslexia-related conflict processing literature into a more language-related domain.
(4) Are there general differences between TD children and children with dyslexia in processing of visual stimuli? Deficits in general visual processing and visual attention are frequently assumed in dyslexia (Facoetti and Turatto, 2000; Stein, 2014), however, this question is still severely discussed (Wimmer and Schurz, 2010). The visual interference control experiment allowed us to examine whether there are general visual processing deficits in dyslexia or whether the reported deficits are limited to specific domains.

As the conflict in the letter-speech sound interference experiment is based on the automatic activation of letter-speech sound associations, which are expected to be strong and highly automatic in TD German 9-year-olds, but impaired in children with dyslexia (Moll et al., 2016), we expect to find different congruency-related effects in the control and the affected group. In the control group of TD children, we expect to see fast and strong conflict-related effects, reflected in less negative N1 and N2 amplitudes in the incongruent than in the congruent condition. In previous studies, the direction of the conflict-related N1 and N2 amplitude modification was somewhat inconsistent; however, it seems that in auditory paradigms, the conflict reduces amplitudes (Henkin et al., 2010; Yu et al., 2015). Our conflict depends on the activation of auditory information, thus, we expect our paradigm to be more strongly related to the findings of auditory- than visual studies. The cSP is expected to be more positive in the incongruent than in the congruent condition (Yu et al., 2015). Behaviorally, we expect slower RTs in the incongruent than in the congruent condition, reflecting a strong interference effect, at least in the control group. In the group of children with dyslexia, however, letter-speech sound associations might be weak and impaired, as shown in previous ERP-studies (Schulte-Körne et al., 1998; Bishop, 2007; Moll et al., 2016). Thus, speech sounds associated with the letters might not get automatically activated, resulting in less interference and weak or absent conflict-related RT- and ERP-effects.

In the visual interference control experiment, the conflict in the incongruent condition is based on visual aspects of the stimuli. Again, RTs are expected to be slower in the incongruent than in the congruent condition, besides more positive cSP amplitudes in the incongruent compared to the congruent condition. In most visual studies, the N1 and N2 amplitudes are enlarged by visual conflict, thus we expect to find more negative N1 and N2 amplitudes in the incongruent condition. However, whether these effects are comparable between the groups remains unclear. The conflict in the incongruent condition of this experiment is based on visual aspects of the stimuli, thus, we might find similar effects in the groups as visual processing is most probably intact in dyslexia (Wimmer and Schurz, 2010). However, there is also evidence for impaired visual attention in dyslexia (Stein and Walsh, 1997; Facoetti et al., 2003).

MATERIALS AND METHODS

Participants

Participants were selected and recruited in a two-stage selection process based both on classroom screening and individual testing. In the first step, children were selected based on an extensive classroom screening with 1488 children at the end of the 3rd grade. The screening was carried out in 46 primary schools in the rural and urban areas of Munich (Germany). Reading fluency and spelling were assessed by standardized classroom tests (SLS 2–9: Wimmer and Mayringer, 2014; DRT-3: Müller, 2004). Children were classified as reading and spelling impaired (dyslexic group) if they scored at or below the 18th percentile on the reading test and below the 20th percentile on the spelling test. Children with reading and spelling performances between the 25th and 75th percentile were included in the control group.

In addition, a classroom test measuring non-verbal IQ (CFT 20-R: Weiß, 2006) was administered. Only children with a non-verbal IQ $\geq$ 85 were invited for further testings. Further inclusion criteria were German as 1st language, normal or corrected-to-normal vision, absence of neurological deficits and no symptoms of AD(H)D as measured by a standardized questionnaire answered by caregivers (DISYPS-II: Döpfner et al., 2008). All children fulfilling criteria for the dyslexic group were invited for individual testing. For the control group, we invited gender and IQ-matched children from the same classroom and school. Altogether, 163 children (87 control children and 76 children with dyslexia) were invited to individual testings (estimated prevalence rate of 5.11%).

From the invited 163 children plus 1 volunteer (based on word-of-mouth recommendation), 85 children (42 control children and 43 children with dyslexia) gave written consent and took part in the study. Before inclusion into the final sample, reading scores were verified by an individually administered 1-min word and pseudoword reading fluency test (SLRT-II: Moll and Landerl, 2010) in a second selection step. Participants were only included in the study if their reading performance measured by the SLRT-II reflected their reading performance in the screening test (SLS 2-9). In order to be included in the dyslexic group, children had to score below the 18th percentile on at least one subtest of the SLRT-II (word- or pseudoword reading). Children in the control group had to score above the 20th percentile for both subtests.

Altogether, we had to exclude five children from the control group (two children based on their reading scores and three children based on their EEG data including one child who misunderstood the task, one child who had incomplete EEG data and one child who did not have enough artifacts-free ERP segments) and seven children from the dyslexic group (three children based on their high reading scores above the cutoff, and four children based on their EEG data including one child who misunderstood the task, one child who had incomplete EEG data and two children who did not have enough artifacts-free ERP segments).

This resulted in a final overall sample size of 37 children in the control group and 36 children in the dyslexic group. There were no significant differences between the groups in age, intelligence, gender, or handedness (all $ps > 0.49$; see **Table 1**). However, in line with our selection criteria, the groups differed in reading speed and spelling performance (all $ps < 0.001$; see **Table 1**).

The study was approved by the Institutional Review Board of Medical Faculty of the University Hospital Munich and was performed in accordance with the latest version of the Declaration of Helsinki and in compliance with national legislation. Parents and children were informed in detail about the experimental procedures and the aims of the study, and gave their written consent prior to inclusion in the study. Children received vouchers in return for their participation.

Behavioral Measurements

Screening in Classroom Settings

The screening took place in classroom settings within a 3 month time period at the end of grade 3. Reading, spelling and IQ-tests (SLS 2-9, DRT-3 and CFT-20-R) were administered by trained research assistants.

Reading

In the classroom administered reading fluency test (SLS 2-9: Wimmer and Mayringer, 2014; parallel-test reliability $r = 0.95$ and content validity $r = 0.89$ for grade 2) children were asked to read sentences silently and to mark them as semantically correct or incorrect (e.g., "Trees can speak"). After 3 min, the task was terminated and at evaluation, the number of correctly marked sentences was calculated.

Spelling

Spelling was assessed using a standardized classroom test (DRT-3: Müller, 2004; parallel-test reliability $r = 0.92$ and content validity $r = 0.78$). The task consisted of 44 single words which had to be written into sentence frames. The examiner first dictated the word, then read the full sentence, and repeated the dictated word. The number of correctly spelled words was scored. One

TABLE 1 | Descriptive statistics of the groups.

	Control group ($n = 37$)		Dyslexic group ($n = 36$)		*t*-value	*p*-value
	M	*SD*	*M*	*SD*		
Age in years	9.47	0.32	9.50	0.50	0.37	0.71[1]
IQ	110.57	10.59	109.14	13.38	−0.51	0.61[1]
ADHD questionnaire	0.42	0.29	0.50	0.30	1.14	0.26[1]
Handedness (right/left)	32/5		33/3			0.71[2]
Gender (males/females)	20/17		16/20			0.49[2]
Reading speed	52.05	12.85	10.19	8.75	−14.90	0.00[1]
Spelling	57.46	11.82	9.94	6.16	−21.61	0.00[1]
SLRT-II words	54.15	17.35	7.28	6.40	−15.39	0.00[1]
SLRT-II pseudowords	53.60	19.57	12.17	8.58	−11.77	0.00[1]

Means (M) and standard deviations (SD) are reported separately for the groups. IQ is based on the CFT-20-R. The total value of the DYSIPS-II ADHD questionnaire is reported (combined for the three scales; inattention, hyperactivity, and impulsivity). Handedness was estimated by self-report. Reading speed and spelling scores are based on the SLS 2-9 and the DRT-3/DRT-4, respectively and are reported in percentile ranks. SLRT-II scores are reported separately for word- and pseudoword- reading and are measured in percentile ranks.

[1] *t-test for independent samples.*

[2] *Pearson's chi-square test.*

participant with dyslexia did not take part in the screening but volunteered for participation during the individual testing phase at the beginning of grade 4 (see Participants). The screening measure was, therefore, adapted for this child and spelling was assessed by the corresponding version of the test for grade 4 (DRT-4: Grund et al., 2004; split-half reliability $r = 0.92$ and content validity $r = 0.68–0.94$).

CFT-20-R

The German version of the Culture Fair Intelligence Test (CFT 20-R; Weiß, 2006) was administered in order to estimate non-verbal cognitive abilities of the participants without the influence of sociocultural and environmental factors. The test consists of four subtests: Series, Classification, Matrices, and Topology and has a high reliability ($r = 0.92–0.96$) and construct validity (correlation with the "g"-factor $r = 0.78–0.83$).

Individual Assessments

Individual testing was part of a large cognitive and neurophysiological test battery and was divided into three testing sessions on two or three different days. The maximum time interval between the behavioral assessment and the EEG measurement was 96 days (mean: 20.56 days).

Word- and Pseudoword Reading

An individually administered 1-min word and pseudoword reading fluency test (SLRT-II; Moll and Landerl, 2010; parallel-test reliability $r = 0.90–0.94$ and content validity $r = 0.69–0.85$ for grade 3) was used. The test contains a word and pseudoword reading list with items increasing in length and complexity. Children were asked to read each list aloud as fast as possible without making any errors. The relevant measure is the number of correctly read words and pseudowords read within the 1 min time limit.

DYSIPS-II

In order to exclude children with ADHD and estimate attentional problems in our participants, we conducted a short telephone interview with one of the participant's caregiver based on the ADHD questionnaire of the DISYPS-II (Döpfner et al., 2008). The DYSIPS-II is a well-established standardized structured interview for psychiatric disorders in children and adolescents based on DSM-IV and ICD-10 guidelines (Cronbach's $\alpha = 0.87–0.94$ for parental ratings of ADHD symptoms). The ADHD-questionnaire comprises of 20 questions corresponding to the three main dimensions of the ADHD symptomology: attentional deficits, hyperactivity, and impulsivity.

ERP Paradigm and Procedure

During EEG acquisition, children performed two novel experiments, which we named letter-speech sound interference and visual interference task. The experiments were presented block-wise and the presentation order was counterbalanced between participants. The child's task was to indicate by button press whether the visually presented stimuli (pairs of letters or pairs of false fonts) looked exactly the same. There were three experimental conditions in both experiments: (1) the incongruent (e.g., different visual appearance but same phoneme: A-a) and (2) the congruent (e.g., different visual appearance and different phoneme: A-e) condition, which both required a "no"-answer, and (3) the "yes"-answer (e.g., A-A) condition (see **Figure 1**). However, the "yes"-answer condition was only introduced in order to have two answer options resulting in a meaningful task, but it did not bear any theoretical importance. Thus, main analyses were carried out only for the congruent and incongruent "no"-answer conditions but not for the "yes"-answer condition. For the "yes"-answer condition, we report descriptive data only.

In the letter-speech sound interference experiment we used 10 letters (A, B, D, E, F, H, M, N, R, and T) written either in upper or in lower case to build the letter-pairs. These letters were selected because they have visually distinct upper- and lower-case forms (as compared for example to C or K). In the incongruent condition (e.g., A-a), the same letters written once in upper and once in lower case were presented. In this condition, the speech sounds corresponding to the two presented letters were the same, but the visual appearance of the two letters were different. Thus, we expected a conflict between the automatically activated, task irrelevant information (associated speech sounds) and the task relevant information (visual appearance of the letters). In the congruent condition (e.g., A-e), two different letters were presented. Thus, both the speech-sounds associated with the two presented letters (automatically activated, but task irrelevant information) and the visual forms of the two presented letters (the task relevant information) were different, and implied the same answer. In the yes-answer condition (e.g., A-A), the same letters written in the same case were presented (see **Figure 1**).

This procedure resulted in 10 possible letter-pairs in the incongruent condition. In order to keep the visual effects balanced, the letter-pairs were presented both with upper-case to the left (e.g., A-a, M-m) and with lower case to the left (e.g., a-A, m-M) versions, resulting in 20 different stimulus pairs. Each of these stimulus pairs was repeated three times throughout the experiment, thus the incongruent condition consisted of 60 trials altogether. In order to keep the conditions comparable, we chose 10 letter pairs for the congruent condition (out of the 45 possible combinations). In selecting these letter-pairs, we avoided letter-combinations which could have resembled meaningful abbreviations in German and the combination of consonants and vowels, in order to avoid easily pronounceable combinations. These 10 selected letter-pairs comprised one upper- and one lower-case letter, and were presented similarly to the incongruent condition also in their forward (e.g., T-f, A-e) and reversed version (e.g., f-T, e-A). Again, the stimulus pairs were repeated three times, which resulted in a total amount of 60 congruent-trials. Thus, the total amount of trials and the amount of stimulus-repetitions was the same in the incongruent (e.g., A-a) and in the congruent (e.g., A-e) condition. There were 90 trials in the yes-answer condition, 45 of them presented in lower case (e.g., a-a, m-m) 45 of them presented in upper case (e.g., A-A, M-M), which resulted in an average repetition rate of 4.5 of each yes-answer stimulus. The stimulus-repetition rate of this condition was thus somewhat higher than the repetition rate of the congruent and incongruent conditions, and the ratio of

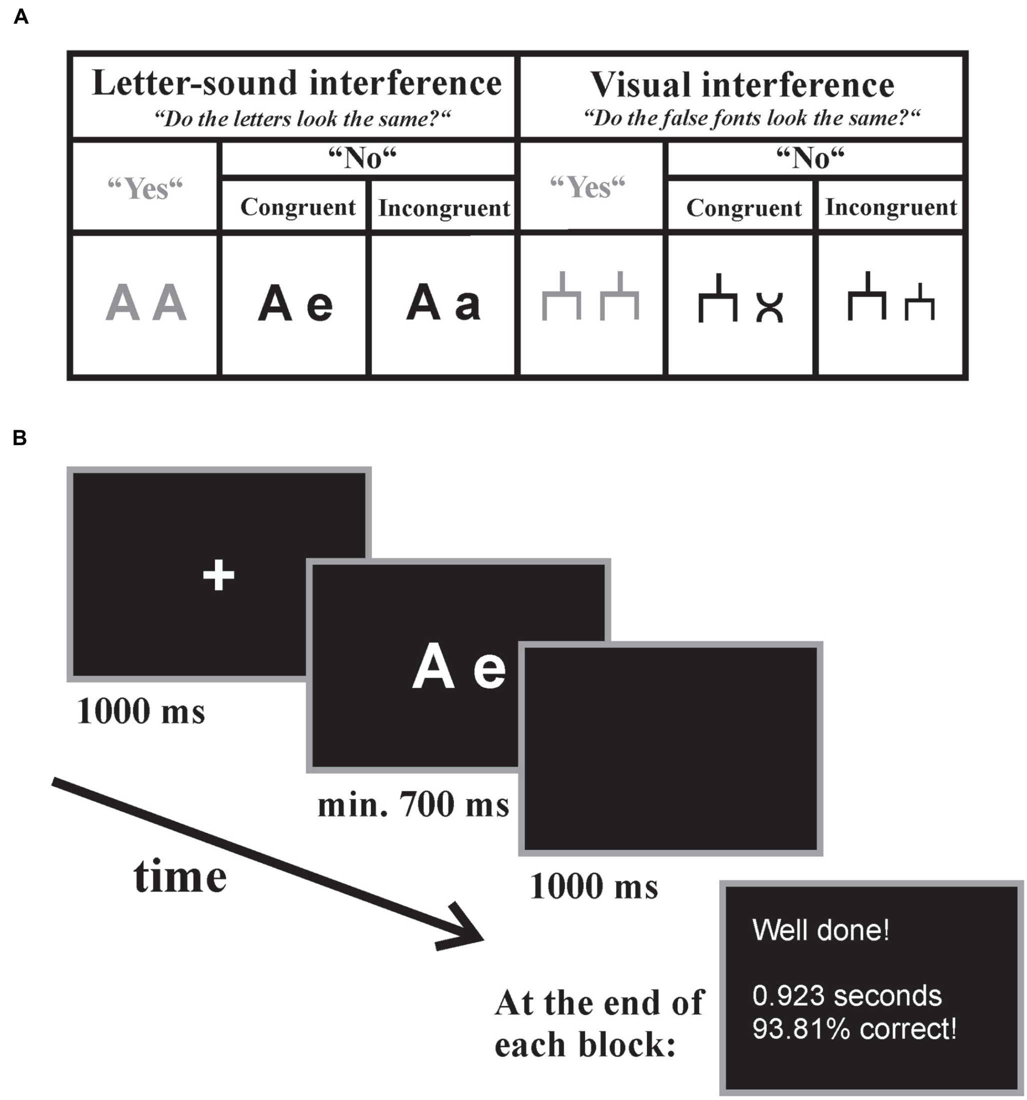

FIGURE 1 | Letter-speech sound interference and visual interference task. (A) Experimental conditions and an example of the presented stimuli in each condition listed separately for the tasks. **(B)** An example trial of the letter-speech sound interference experiment. Participants were instructed to decide via button-press whether the presented stimuli looked visually the same and received feedback about their general performance at the end of each block.

"yes" and "no" answers were 90–120, but since the "yes"-answer condition was not included in the later analysis, the differences between the conditions were not expected to influence the results.

Incongruent, congruent and yes-answer trials were presented in four pseudorandomized lists in an intermixed manner. The pseudorandomization ensured that no more than four consecutive trials had the same answer ("yes" or "no"), preventing tendencies to automatic responses. The four pseudorandomized lists were randomly assigned to the participants within each group. To ensure that the participants understood the task, the experiment was preceded by a short practice block (consisting of eight trials; two congruent, two incongruent, and four "yes"-answer trials). Each experiment was divided into two blocks with a short break in between, thus the whole processing comprised four blocks (two blocks in the letter-speech sound interference and two blocks in the visual interference experiment). One block comprised 105 stimuli and lasted 5 min, thus the whole procedure took approximately 20 min. After each break, and at the end of the experiment, participants received feedback about their general performance in the present block (percentage of correct answers and response speed in ms).

In the visual interference control experiment we assigned a false font (for an example see **Figure 1**) to each letter, thus we used 10 different false fonts presented either in the relatively big (equivalent to the upper-case letters) or in the relatively small size (equivalent to the lower-case letters) to build the false font-pairs. In the congruent condition, two different fonts were presented. In the incongruent condition, the same fonts were presented in big and small sizes. Thus, in this condition there was a visual conflict based on the visual similarity of the objects. Again, in the "yes"-answer condition, the same false fonts in the same size were presented (see **Figure 1**).

All stimuli (both letters and false fonts) were presented in white on black background in the center of a 24 inches monitor with a refresh rate of 60 Hz and a high resolution of 1920 × 1080 using E-Prime® 2.0 software (Psychology Software Tools, Inc.). The computer screen was placed 70 cm in front of the children which resulted in a vertical visual angle of 1.03–1.38° and in a horizontal visual angle of 2.20–3.90° depending on the presented stimuli. Each trial started with a fixation cross (Arial, 52, bold) which remained on the screen for 1000 ms. Afterward, the stimulus pairs appeared (letters: Arial, 52, bold). Children were instructed to respond by pressing the right button for "yes" if the stimuli looked visually the same and the left button for "no" if the stimuli did not look the same on a two-key keyboard as fast as possible. The stimuli remained on the screen for at least 700 ms or until response in case it took longer. The next trial started after a 1000 ms-long blank screen. At the end of each block participants received feedback about their performance (see **Figure 1**).

ERP Recording and Analysis

During the experiments, continuous EEG was recorded with an Electrical Geodesics Inc (2016) 128-channel system (see **Figure 2** for a schematic illustration of the electrode net) with a sampling rate of 500 Hz and Cz as the reference electrode (Electrical Geodesics Inc, 2016; EGI, Eugene, OR, USA; Tucker, 1993). Impedance was monitored throughout the recording and kept below 50 kΩ. Further processing steps were performed with BrainVision Analyzer 2.0 (Brain Products GmbH, Gilching, Germany).

After visual inspection of the data, the continuous EEG was filtered (low cutoff: 0.5 Hz, time constant: 0.3, 12 dB/Oct; high cutoff: 40 Hz, 12 dB/Oct; notch filter: 50 Hz) and EOG artifacts were removed by semiautomatic ocular correction, using an ICA algorithm as implemented in BrainVision Analyzer 2.0 (Slope Mean, over the whole data, ICA with infomax algorithm, total squared correlations to delete: 30%; Gratton et al., 1983; Plank, 2013). Other artifacts were excluded automatically (gradient criteria: more than 50 μV difference between two successive data points or more than 100 μV difference in a 100 ms window; absolute amplitude criteria: amplitudes exceeding +150 or −150 μV; low activity criterion: less than 0.5 μV activity in a 100 ms window) and the EEG was re-referenced to the average of the mastoids.

The data was then segmented into epochs from −200 to 1000 ms relative to stimulus onset. The 200 ms pre-stimulus period was used for baseline correction. Afterward, the individual ERPs were averaged separately for each experimental condition and each participant group. Only correct trials were analyzed. In order to be included into the final analysis, participants had to have a minimum of 30 correct, artifact-free trials in each experimental condition. The average number (M [SD]) of accepted trials for the control group was 56 [2.53] and 57 [2.55] in the letter-speech sound interference experiment and 55 [4.01] and 56 [3.42] in the visual interference experiment (incongruent and congruent condition, respectively). For the dyslexic group, there were on average 54 [3.95] and 55 [4.29] accepted trials in the letter-speech sound interference experiment and on average 53 [2.99] and 55 [3.04] accepted trials in the visual interference experiment (incongruent and congruent condition, respectively). Based on non-parametric Mann–Whitney-*U*-test, the difference between the control and the dyslexic group in the average number of accepted trials was significant (all $ps = 0.012–0.048$). The number of accepted trials was somewhat higher in the control than in the dyslexic group. However, please note that the average number of accepted trials is at a very high level in both groups, consistently above 53 out of a maximum of 60 (corresponding to 89%), which can be considered as being close to ceiling.

Based on previous conflict-related ERP studies, we expected to observe the biggest N1 and N2 amplitude differences over frontal sites. The visual inspection of the data confirmed this assumption, thus, we defined our region of interest (ROI) over frontal sites, including the electrodes 3, 4, 5, 6, 10, 11, 12, 16, 18, 19, 20, 23, 24, 118, and 124 (see **Figure 2**). We searched for the most negative peak (local maximum) in the time window between 70 and 140 ms for the N1 and in the time window between 280 and 380 for the N2. Mean peak amplitudes and latencies were exported for each electrode of the above defined frontal ROI. The cSP is commonly observed over parietal regions, which was confirmed by visual inspection of our data, thus we defined a parietal ROI including the electrodes 61, 62, 67, 72, 77, and 78 (see **Figure 2**). For statistical analysis of the cSP, we exported the mean amplitude value for each electrode of the ROI between 500 and 900 ms. After the above defined exportations, the values of individual peak amplitudes, latencies and mean values were averaged over the electrodes included in the frontal and parietal ROI, respectively.

As there is evidence that cortical activation in letter-processing tasks might be less left lateralized in children with dyslexia (Moll et al., 2016), we considered the inclusion of the factor laterality in our analysis by building separate ROIs in the left and right hemisphere. In order to examine possible laterality differences between the groups, we conducted exploratory analysis comparing N1 and N2 amplitudes between the groups at different frontal locations (left, right, and central side). We found no laterality by group interaction effects ($p > 0.19$ and $p > 0.36$ for the N1 and N2 amplitudes, respectively), thus we did not consider laterality in further analysis.

Statistical Analysis

Before statistical analysis of the behavioral data, RTs were outlier-corrected in two steps. In the first step, based on the distribution of all RTs across all participants, extreme values below 200 ms and above 10,000 ms were excluded. Afterward, RTs deviating more than 3 SD from the individual mean of each subject were removed. This processing resulted in the exclusion of 2.13% of the RTs in the letter-speech sound interference and the exclusion of 2.12% of the RTs in the visual interference task. Only correct answers were analyzed.

For the analysis of both the RT and EEG data, we computed mixed-model repeated measures ANOVAs including the within-subject factor *congruency* (congruent vs. incongruent condition) and the between-subject factor *group* (control group vs. dyslexic

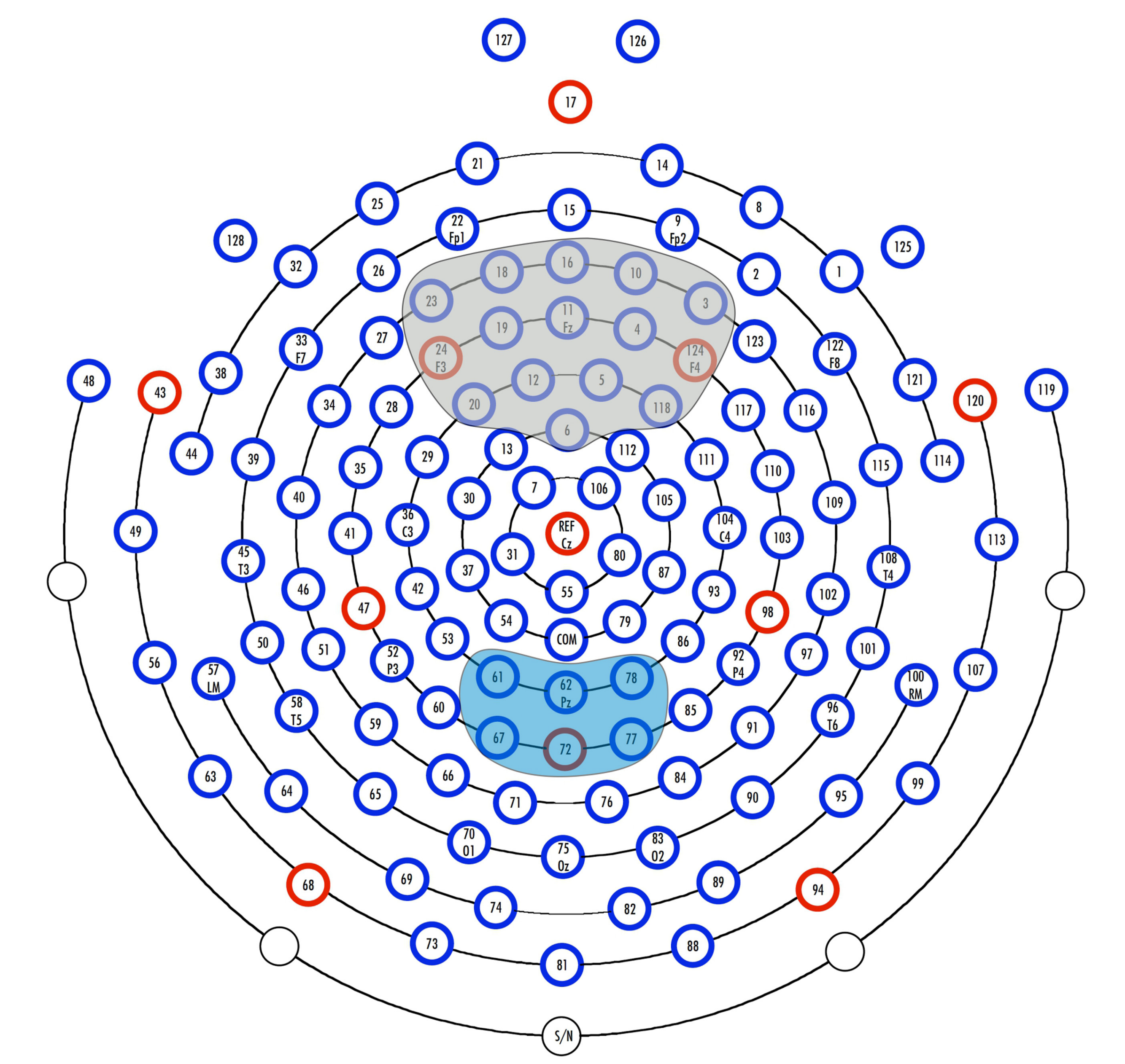

FIGURE 2 | Illustration of the 128-channel system (Electrical Geodesics, Inc.) and the examined regions of interest. The electrodes included in the parietal ROI of the conflict slow potential (cSP) are marked in blue. Electrodes included in the fronto-central ROI of the N1 and N2 are gray.

group) with an alpha level of 0.05. Significant interactions involving the factor group were examined with two-sided *post hoc* *t*-test.

The reliability of our novel paradigm was assessed using split-half correlations (Pearson's coefficient; two-sided) of the mean RTs of the individual conditions. Correlation between the mean RTs of the first half and second half of the trials was consistently high in every condition; $r = 0.91$, $p < 0.001$ for the incongruent and $r = 0.91$, $p < 0.001$ for the congruent condition in the letter-speech sound interference task, and $r = 0.85$, $p < 0.001$ for the incongruent and $r = 0.91$, $p < 0.001$ for the congruent condition in the visual interference task.

RESULTS

Behavioral Data

Error Rates

Error rates were very low in both the control and the dyslexic group. In the control group, the average error rate was 3.78% [3.13] and 0.95% [1.28] in the letter-speech sound interference experiment and 4.59% [3.82] and 1.98% [2.60] in the visual interference experiment (incongruent and congruent condition, respectively). For the dyslexic group, there was an average error rate of 6.02 and 3.52% in the letter-speech sound interference experiment and an average error rate of 6.90% [4.61] and 3.52% [3.42] in the visual interference experiment (incongruent and congruent condition, respectively). These high accuracy levels can be considered as being at ceiling. This might explain that even though the actual group difference between the error rates was very small, it still resulted in a significant main effect of group both in the letter-speech sound interference, $F_{(1,71)} = 11.92$, $p < 0.01$; $\eta_p^2 = 0.14$ and in the visual interference experiment, $F_{(1,71)} = 7.55$, $p < 0.01$; $\eta_p^2 = 0.10$.

We further found a strong congruency effect in both, the letter-speech sound interference, $F_{(1,71)} = 35.27$, $p < 0.001$; $\eta_p^2 = 0.33$, and the visual interference experiment, $F_{(1,71)} = 35.33$, $p < 0.001$; $\eta_p^2 = 0.33$. Accuracy rates were higher in the congruent than in the incongruent condition in both experiments. There was no significant interaction between congruency and group, neither in the letter-speech sound interference ($p = 0.71$), nor in the visual interference experiment ($p = 0.45$).

The average error rate in the "yes"-answer condition was 3.63% [3.21] and 5.62% [4.29] in the control group, and 5.22% [3.14] and 8.49% [5.17] in the dyslexic group (for the letter-speech sound interference and visual interference experiment, respectively).

Response Times

There was no RT difference between the groups neither in the letter-speech sound interference, $F_{(1,71)} = 2.04$, $p = 0.16$, nor in the visual interference experiment, $F_{(1,71)} = 0.84$, $p = 0.36$. However, there was a strong congruency effect in both the letter-speech sound interference, $F_{(1,71)} = 7.86$, $p < 0.01$; $\eta_p^2 = 0.10$, and the visual interference task, $F_{(1,71)} = 13.12$, $p < 0.01$; $\eta_p^2 = 0.16$. RTs were faster in the congruent than in the incongruent condition in both experiments (see **Figure 3**). There was no significant interaction between congruency and group, neither in the letter-speech sound interference ($p = 0.33$), nor in the visual interference experiment ($p = 0.75$).

ERP Data

Event-related potential waveforms including the N1, N2, and cSP components are depicted in **Figure 4**, separately for the letter-speech sound interference and visual interference experiments. Group mean of amplitudes and latencies are reported in **Table 2**.

Letter-Speech Sound Interference Experiment

N1 Amplitudes and Latency

We found no main effect of group or congruency with respect to N1 amplitudes (all ps > 0.34). However, there was a significant group by congruency interaction, $F_{(1,71)} = 5.42$, $p = 0.02$; $\eta_p^2 = 0.07$. *Post hoc t*-test between the conditions revealed a significant difference between congruent and incongruent trials in the control group, $t_{(36)} = 2.12$, $p = 0.04$; $\eta_p^2 = 0.11$. Amplitudes were less negative in the incongruent than in the congruent condition. There was no significant difference between the conditions in the dyslexic group, $t_{(35)} = 1.09$, $p = 0.28$; $\eta_p^2 = 0.03$.

There were no significant main effects or interaction with respect to N1 latencies (all ps > 0.15).

N2 Amplitudes and Latency

There were no significant main effects or interactions with respect to N2 amplitudes and latencies (all ps > 0.40).

Conflict SP Mean Amplitudes

We found no main effect of group or congruency (all ps > 0.27) but a significant group by congruency interaction, $F_{(1,71)} = 4.39$, $p = 0.04$; $\eta_p^2 = 0.06$. The difference between the congruency conditions approached significance in the control group, $t_{(36)} = 2.01$, $p = 0.05$; $\eta_p^2 = 0.10$. Mean amplitudes tended to be higher in the incongruent compared to the congruent condition. There was no significant difference between the conditions in the dyslexic group, $t_{(35)} = 0.96$, $p = 0.35$; $\eta_p^2 = 0.03$.

Visual Interference Experiment

N1 Amplitudes and Latency

There were no significant main effects or interactions with respect to N1 amplitudes and latencies (all ps > 0.12).

N2 Amplitudes and Latency

There was a main effect of congruency with respect to N2 amplitudes, $F_{(1,71)} = 4.97$, $p = 0.03$; $\eta_p^2 = 0.07$, but no other significant effect or interaction (all ps > 0.58). N2 amplitudes were less negative in the incongruent than in the congruent condition.

There were no significant main effects or interaction with respect to N2 latencies (all ps > 0.10).

Conflict SP Mean Amplitudes

We found a significant main effect of congruency, $F_{(1,71)} = 10.33$, $p < 0.001$; $\eta_p^2 = 0.13$. Mean amplitudes were higher in the incongruent than in the congruent condition. There was no other significant effect or interaction (all ps > 0.40).

DISCUSSION

The aim of the present study was to investigate the degree of automatization in letter-speech sound processing in children with dyslexia compared to TD children. For this reason, we implemented a newly designed letter-speech sound interference experiment and a visual interference control experiment while recording EEGs. In the letter-speech sound interference experiment, children were presented with two letters, and had to decide whether the two letters looked visually the same. In the incongruent condition, where the same letter was presented twice, once in upper and once in lower case (e.g., A-a), we expected to find a conflict between the visual information (the visual characteristics of A-a) and the automatically activated phonological information (both letters activate the sound /a/). The size of this conflict was supposed to reflect letter-speech sound automatization strength. In the congruent condition

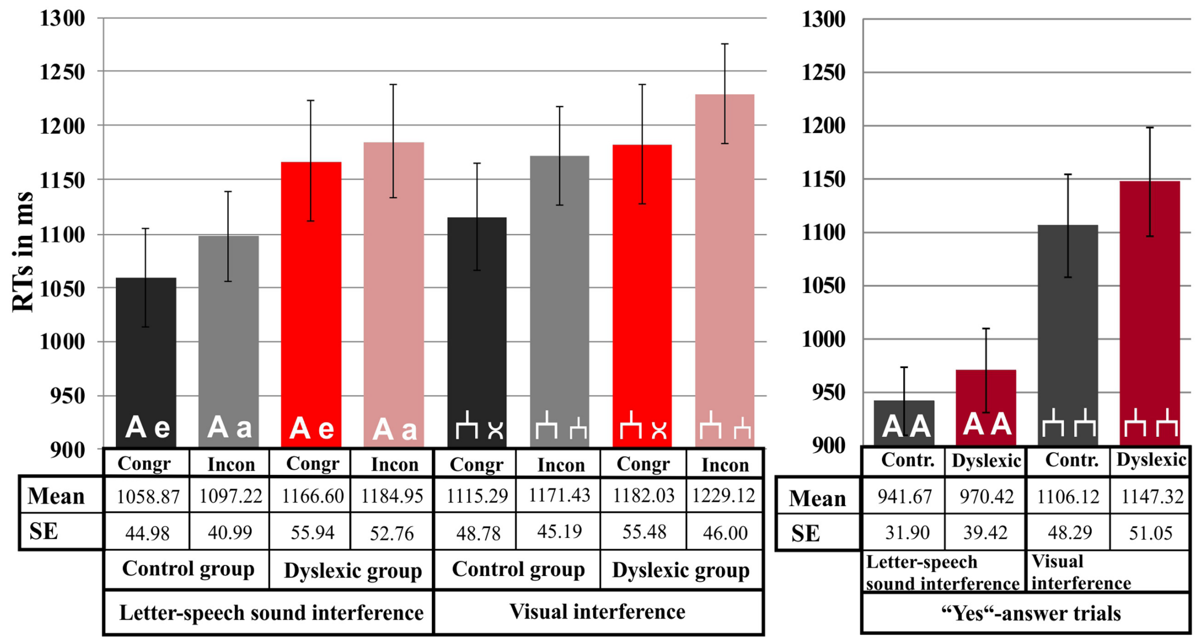

FIGURE 3 | Response time results. Mean values are depicted separately for each experiment, condition and group. Error bars represent the standard error of mean.

(e.g., A-e) in turn, no conflict was expected. In the visual interference experiment, the conflict was based purely on the visual similarity of the stimuli, thus this experiment served as a control experiment. We were interested in four questions which we are going to discuss now: (1–2) Are there any differences between children with dyslexia and TD children in the automatization degree of letter-speech sound processing and in the temporal sequence of letter-speech sound association processes? These questions are discussed in the section letter-speech sound interference experiment. (3–4) Do children with dyslexia have impairments in visual attention and visual conflict processing, and if so, are these impairments general or restricted to letter processing involving visual-verbal access? These questions are discussed in the section visual interference experiment.

Letter-Speech Sound Interference Experiment – Measuring the Automatization Strength of Letter-Speech Sound Associations

We found a strong interference effect, reflected in the RTs of all participants. As expected, RTs were slower in the incongruent than in the congruent condition. Thus, the experimental manipulation worked as intended: speech sounds associated with the presented letters got automatically activated, which resulted in a conflict between the task-relevant and the task-irrelevant information as evident by slowed-down RTs. Furthermore, in the TD control group we found less negative N1 and more positive cSP amplitudes in incongruent compared to congruent trials. However, there was no difference between the N2 amplitude heights of incongruent and congruent trials.

The fronto-central N1, measured in our experiment 70–140 ms after stimulus presentation, is related to conflict sensory detection (Yu et al., 2015). As N1 amplitudes were modified in the control group, we conclude that the conflict between the phonological (speech sound) and visual information emerged in the control group in a very early time window within the first 140 ms. This implies that in TD 9-year-olds, letters activated their corresponding speech sounds in a highly automatic manner, almost immediately. The direction of the conflict-related N1 amplitude modification was thereby the same as in previous studies using an auditory Stroop-paradigm: N1 amplitudes were less negative in incongruent than in congruent trials (Lew et al., 1997; Henkin et al., 2010; Yu et al., 2015). This similarity to the findings of auditory paradigms reinforces the assumption that the conflict in our letter-speech sound interference paradigm was really based on the automatic activation of phonological information.

Importantly, we found no evidence of conflict-related N1 amplitude effects in the dyslexic group. Thus we assume that in children with dyslexia speech sounds associated with the letters were not activated at this early time point (140 ms after stimulus presentation).

The parietal cSP, measured in our study 500–900 ms after stimulus presentation, is linked to conflict resolution and response selection processes (Yu et al., 2015). As expected, cSP amplitudes were higher in the incongruent than in the congruent condition within the TD group (Donohue et al., 2012; Yu et al., 2015). However, there was again no evidence of conflict-related amplitude effects in the group of children with dyslexia. Thus,

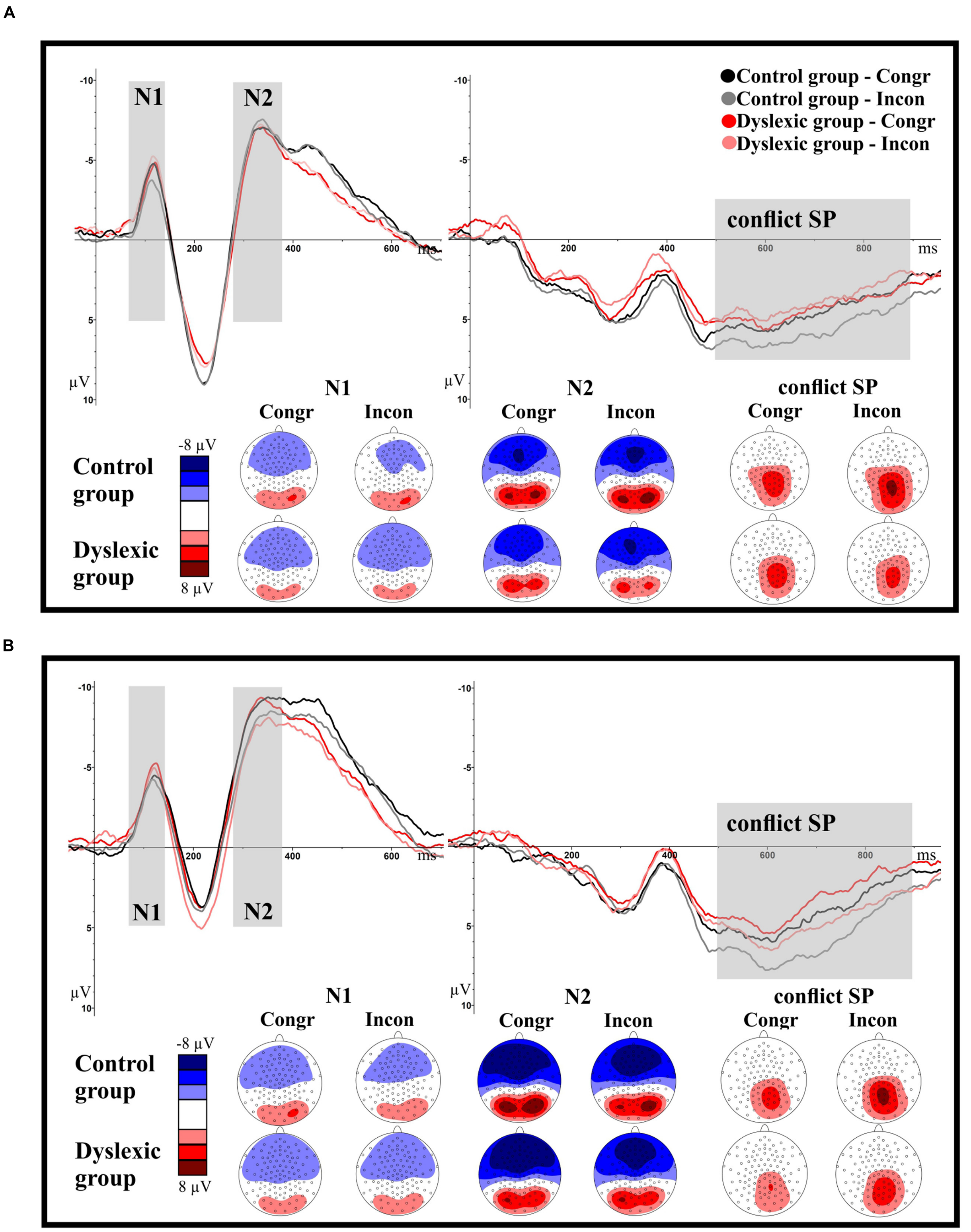

FIGURE 4 | Illustration of the grand-average ERP waveforms depicted separately for the fronto-central (N1, N2) and the parietal ROIs (cSP) and the letter-speech sound interference and visual interference experiments. The time windows selected for the components N1 (70–140 ms), N2 (280–380 ms) and cSP (500–900 ms) are highlighted in gray. Negativity is depicted upward. **(A)** ERP components (averaged per group and condition) in the letter-speech sound interference experiment. **(B)** ERP components (averaged per group and condition) in the visual interference experiment.

it seems that speech sounds associated with letters did not get automatically activated until 900 ms after stimulus onset in 9-year-old children with dyslexia.

However, children with dyslexia showed congruency effects in the behavioral measure. In both groups, RTs were slower in the incongruent than in the congruent condition. Thus, as there was a behavioral effect of conflict in children with dyslexia, speech sounds must have been activated at some point in time, most probably after 900 ms of letter presentation. This finding is in line with previous electrophysiological investigations: electrophysiological studies implementing an audiovisual MMN paradigm have found delayed letter-speech sound association effects in children with dyslexia compared to TD children (Froyen et al., 2011; Moll et al., 2016). As activation of speech sounds was not necessary for solving the letter-speech sound interference task, the delayed association observed in the ERP data might not have hampered task performance, which might explain why there was no overall RT difference between the groups. However, delayed letter-speech sound association might impact on RTs in reading related tasks where letter-speech sound association are consistently required during task performance.

Finally, we need to discuss the lack of a conflict-related N2 effect. Based on the findings of Yu et al. (2015) we expected to find less negative N2 amplitudes in incongruent compared to congruent trials, even though findings on conflict-related N2 amplitude modifications are still very mixed: there are studies reporting enhanced conflict-related N2 amplitudes (van Veen and Carter, 2002a,b; Yeung et al., 2004; Johnstone et al., 2009), or a null result (Henkin et al., 2010). We have two possible explanations, which might account for the different findings: first, we have to consider the differences between the designs of the two paradigms: in the study of Yu et al. (2015) the stimuli were spoken Chinese words, presented auditory. In our study, however, we displayed single letters and false fonts, visually. As proposed in the three stages cognitive control model for auditory Stroop task (Yu et al., 2015), the N2 reflects the conflict identification stage, including the categorization and coding of the conflict information. As our letter-stimuli were quite simple, it might be possible that no categorization was needed or that the categorization process was faster than in other paradigms and thus, already fully accomplished at the time point of the N2. A second possible explanation may be that there was a big difference between the age of our participants and the age of the participants in Yu et al.'s (2015) study. We examined 9-year-old children, whereas the participants of Yu et al. (2015) were healthy students. As electrophysiological studies investigating auditory Stroop-paradigms in children are missing, we cannot rule out that conflict-related N2 amplitude effects change with age. In order to examine this possible explanation, further studies comparing different age groups are needed.

Taken together, the letter-speech sound interference paradigm is useful to measure automatization strength of letter-speech sound associations. The experimental manipulation resulted in strong behavioral effects in both groups and fast and strong neurophysiological correlates in the control group. Furthermore, we revealed neurophysiological differences between TD children and children with dyslexia in the automatization strength of letter-speech sound associations in a relatively naturalistic setting of sole visual letter presentations. Speech sounds associated with letters were activated very fast in TD children; the first effects being present already within 140 ms. In contrast, children with dyslexia did not show neurophysiological evidence of automatic letter-speech sound activation effects. Thus, we can conclude that letter-speech sound associations are highly automatic in TD 9-year-olds, but are less automatized in children with dyslexia.

Visual Interference Experiment – Measuring Visually Based Conflict Processing

Response times were slower in the incongruent than in the congruent condition, thus there was a strong interference effect. Also, N2 amplitudes were less negative in incongruent than in congruent trials, and cSP amplitudes were more positive in incongruent than in congruent trials. Thus, we can conclude that the experimental manipulation successfully induced conflict. However, there was no difference between the N1 amplitudes of incongruent and congruent trials, and there was no difference between the groups in the behavioral and ERP-effects of conflict.

The finding of increased cSP amplitudes in incongruent trials matches the results of existing studies (Liotti et al., 2000; Larson et al., 2009). However, the finding of less negative N2 amplitudes in incongruent trials compared to congruent trials is contradictory to previous findings. Neurophysiological studies implementing the flanker task reported more negative N2 amplitudes in incongruent than in congruent trials (Yeung et al., 2004; Johnstone et al., 2009).

The reason for this discrepancy between our finding and the findings of the flanker task studies might be that the flanker task – although it is implemented in order to induce visual and response conflict, which makes it in some ways comparable to our study – has a completely different design than our study. It uses flanker-stimuli to induce conflict (e.g., $> > > > >$ or $> > < > >$) whereas we presented two false fonts side by side. Thus, the conflict of the flanker task is determined by the suppression of flankers in the periphery, whereas our conflict is based solely on visual similarity. Another explanation might be the difference between the paradigms in their definition of congruency. In our visual interference experiment, congruent trials are defined as congruent, because of an overarching dimension of congruency; the false fonts look "different," and the required answer is also "different." In contrast, the congruency in the flanker task experiments is based on the similarity of the target stimulus to the flankers. Thus, our congruent condition might be probably stronger comparable with the incongruent condition of the flanker task, where flankers are also perceptually and categorically different from their targets. As our study is the first to use this design, further studies are needed to clarify this issue. Based on our findings, we assume that visual conflict, implemented in the way as in our visual interference experiment (i.e., based purely on visual similarity) results in diminished N2 amplitudes. This assumption is supported by the fact that the

TABLE 2 | Means of peak amplitudes and latencies reported separately for the groups and conditions.

		Control group		Dyslexic group	
		Incon	**Congr**	**Incon**	**Congr**
Letter-speech sound interference					
N1	Amplitude	−3.38 (2.92)	−4.56 (3.43)	−4.63 (3.03)	−4.15 (3.06)
	Latency	111.37 (9.42)	112.62 (10.65)	113.94 (9.53)	115.37 (9.11)
N2	Amplitude	−8.01 (5.97)	−7.74 (5.37)	−7.51 (5.37)	−7.34 (5.22)
	Latency	337.17 (18.59)	334.97 (19.81)	336.40 (14.87)	337.15 (16.60)
cSP	Mean amplitude	5.97 (5.08)	4.85 (4.51)	4.05 (4.31)	4.59 (3.94)
Visual interference					
N1	Amplitude	−4.17 (3.47)	−4.18 (3.20)	−4.33 (3.00)	−4.78 (3.69)
	Latency	112.75 (12.43)	114.08 (10.77)	116.69 (7.51)	116.43 (10.04)
N2	Amplitude	−9.10 (7.11)	−9.91 (7.53)	−8.37 (5.59)	−9.71 (5.47)
	Latency	340.52 (16.80)	337.68 (16.93)	341.84 (15.99)	337.74 (18.33)
cSP	Mean amplitude	5.82 (7.23)	4.15 (5.32)	4.72 (3.32)	3.34 (3.92)

Amplitudes are measured in μV, latencies in ms. Standard deviations are reported in brackets.

directionality of the conflict related N2 amplitude modification might change with the properties of the presented stimuli (e.g., less negative in Yu et al., 2015; more negative in Johnstone et al., 2009).

Importantly, there were no differences between the groups in the direction and extent of the conflict-related behavioral N2 and cSP effects. Visual conflict resulted in longer RTs, diminished N2 and increased cSP amplitudes in both groups. These findings differ from the results of Mahé et al. (2014), who found impaired conflict monitoring and conflict resolution processes in a group of dyslexic adults, reflected in reversed N1 and missing N2 and P3b effects when compared to controls. One possible explanation for the discrepant findings could be that subclinical attentional deficits were not considered in the (Mahé et al., 2014) study. Even though they excluded participants with a diagnosis of ADHD, they did not assess attentional problems in their participants. Individuals with dyslexia often show subclinical problems of inattention, hyperactivity and impulsivity, even though they might not fulfill diagnostic criteria for ADHD (Smith and Adams, 2006). In order to control for subclinical problems of inattention, hyperactivity and impulsivity we explicitly assessed those symptoms. Importantly, our groups did not differ with respect to these symptoms. Another explanation for the discrepant findings is that, as already discussed above for the N2, there was a huge difference between the design of our and Mahé et al.'s (2014) experiment. Mahé et al. (2014) implemented a flanker task, whereas we displayed false fonts. The conflict of the flanker task is induced by the need for flanker suppression, and thus implies the automatic shifting of attention toward stimuli according to the congruency of flankers. For this reason, the findings of Mahé et al. (2014) can mainly be explained by difficulties of the dyslexic group in attentional shifting and flanker suppression. Our study, in contrast, measured visual conflict processing on a more general level based on sole visual similarity without attention shifting. Thus, based on our results we conclude that visual conflict processing is not impaired in dyslexia. However, we cannot exclude that children with dyslexia might have impairments in attentional shifting and suppression of flankers. This interpretation is similar to the conclusions of Bednarek et al. (2004), who also reasoned that TD children and children with dyslexia did not differ in their general perceptual and attentional abilities but are impaired in specific domains, such as narrowing the focus of attention and the inhibition of flanker interference. However, as our study is among the first electrophysiological investigations on conflict control processing in dyslexia, findings in this domain are still very rare. In order to reinforce the above assumption, further investigations are needed.

Finally, we would like to discuss the lack of conflict related N1 effects, which contradicts previous findings. Visual conflict studies implementing the flanker task reported increased N1 amplitudes in incongruent compared to congruent trials (Yeung et al., 2004; Johnstone et al., 2009). We assume that the discrepancy can be explained by methodological differences. False fonts are unknown and visually more complex than the arrows in the flanker task. Thus, visual processing and conflict detection are likely to be slower in the visual interference task than in the flanker task. This is likely to result in a delay of the conflict related effects, resulting in conflict-related modulations in the N2 but not in the N1 amplitude.

To summarize, the results of the visual interference experiment suggest no visual conflict processing deficits in dyslexia. Visual conflict had comparable behavioral and neurophysiological effects in children with dyslexia and TD children. However, studies examining the neurophysiological underpinnings of conflict processing in dyslexia are still very rare, thus our findings need to be replicated.

Limitations

Our study sample was very homogenous, consisting of mostly 9- and 10-year-old children (age range: 8.42–11.25). Although a homogenous sample increases the power of statistical tests, it has a negative impact on the generalizability of the results. It is important to consider age-related differences, especially when studying developmental disorders. It might be possible that the development of automatized letter-speech sound associations is only delayed but not permanently impaired in children with dyslexia. Thus, further longitudinal studies examining the neurophysiological development of letter-speech sound association in dyslexia are needed.

It must be considered that our participants were all German-speaking. As the German language is characterized as a shallow orthography with very consistent letter-speech sound correspondences, it is possible that the effects of our letter-speech sound interference paradigm are stronger in this population. In deep orthographies, as for example in English, letter-speech sound associations might not always be unambiguous. Especially vowels are often pronounced in various ways in English. Thus, for the implementation of the letter-speech sound interference paradigm in English-speaking populations, the application of consonants might be more suitable. This assumption is strengthened by the findings of Posner and Mitchell (1967), who found that RTs indicating the physical identity of the objects were slowed by the same name only for the letter-pairs B-b and C-c, but not for the letter-pairs A-a and E-e, although this finding has already been challenged (Carrasco et al., 1988). Cross-linguistic studies might help to clarify the question of generalizability of these findings.

CONCLUSION

The letter-speech sound interference paradigm has proved to be a good neurophysiological paradigm to examine automatization strength of letter-speech sound associations in TD children and children with developmental dyslexia. Our results point to highly automatic letter-speech sound associations in TD 9-year-old children, whereas letter-speech sound associations seem to be less automatic in children with dyslexia.

The visual interference paradigm extended neurophysiological findings on visual conflict processing in developmental dyslexia. Children with dyslexia and TD children were comparable in the neurophysiological and behavioral visual incongruency effects, thus, we did not confirm the assumption of a general impairment in conflict control processing in dyslexia.

AUTHOR CONTRIBUTIONS

KL, GS-K, and KM were involved in the conception and design of the study. SB, JB, GS-K, and KM developed the methods. SB and KM acquired the data. SB, JB, and KM performed the analyses. SB and KM wrote the first version of the manuscript. All authors commented on the manuscript and approved the final version of the manuscript.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Ich, Sarolta Bakos, erkläre hiermit an Eides statt, dass ich die vorliegende Dissertation mit dem Thema **„Neurophysiologische Korrelate der Worterkennung bei Kindern mit isolierter Lese- und/oder Rechtschreibstörung“** selbstständig verfasst, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

Ich erkläre des Weiteren, dass die hier vorgelegte Dissertation nicht in gleicher oder in ähnlicher Form bei einer anderen Stelle zur Erlangung eines akademischen Grades eingereicht wurde.

_München, 21.02.2019______ ______________________________

Ort, Datum Sarolta Bakos

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