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Naming processes in reading and spelling disorders: An electrophysiological investigation

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HIGHLIGHTS

- Neurophysiology (event-related potentials) of naming processes in reading (RD; F 81.0) and spelling disorder (iSD; F 81.1).
- Impaired lexical access in RD compared to typically developing (TD) children, reflected in a reduced P2 amplitude.
- Comparable neurophysiological naming processes in TD and iSD.

ABSTRACT

Objective: Reading fluency deficits characteristic for reading disorders (RD; F81.0) have been shown to be strongly associated with slow naming speed (e.g. in rapid automatized naming tasks). In contrast, children with an isolated spelling disorder in the context of unimpaired reading skills (iSD; F81.1) show naming speed task performances that are similar to typically developing (TD) children. However, the exact nature of the naming speed deficit and its relation to RD and the question whether children with iSD are also on the neurophysiological level similar to TD children is still unresolved.
Methods: The time-course and scalp topography of event-related potentials (ERP) activity recorded during a delayed digit-naming task was investigated in ten-year-old children with RD and iSD compared to a TD group.
Results: ERP activity differed between the RD and the TD group at around 300 ms after stimulus presentation (left occipito-temporal P2). In contrast, there were no neurophysiological differences between the TD and the iSD group. The P2 component correlated with behavioural performance on the RAN task.
Conclusions: Slow naming speed in RD might result from a slowed-down access and prolonged processing of the word (lexical) form.
Significance: The study establishes a relation between neurophysiological processes of naming tasks and RD.

1. Introduction

Developmental dyslexia is a heterogeneous disorder, characterized by different deficit profiles. The ICD-10 diagnostic system differentiates between specific reading disorder (F 81.0, also called dyslexia; prevalence rate of 7–8%) and specific spelling disorder (F81.1; prevalence rate of 6–7%; Dilling et al., 2008; Moll and Landerl, 2009; Moll et al., 2014; World Health Organization, 2004). The differentiation between deficits in reading and deficits in spelling is even more distinct in DSM-5 and ICD-11, differentiating between a developmental learning disorder with impairment in reading and a developmental learning disorder with impairment in written expression (American Psychiatric Association, 2014; World Health Organization, 2018). Deficits in reading comprise problems in reading, accuracy, fluency, or comprehension. In orthographies with more consistent grapheme-phoneme correspondences, word reading accuracy is close to ceiling after one year of reading instruction (Seymour et al., 2003; Wimmer, 1993). Thus, word reading deficits are mainly characterized by deficits in

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reading fluency rather than reading accuracy (Schulte-Körne, 2010; 2011). As a consequence, the diagnosis of reading disorder (F 81.0) in consistent orthographies is based on deficits in reading speed rather than accuracy. A spelling disorder (F 81.1) is characterized by a significantly increased number of spelling errors and difficulties in the correct implementation of orthographic rules in writing (Schulte-Körne, 2010; World Health Organization, 2004). These difficulties in acquiring adequate literacy skills have been shown to negatively impact on academic and professional careers as well as on psychological well-being. Reading and spelling disorders might lead to fears of failure in school or social situations, and eventually to depression (Schulte-Körne, 2010).

Importantly, the differentiation between spelling and reading disorder is also reflected in different cognitive and neurophysiological deficit profiles associated with spelling versus reading fluency problems (Bakos et al., 2018; Banfi et al., 2017; Mehlhase et al., 2018; Moll and Landerl, 2009; Wimmer and Mayringer, 2002; Wimmer and Schurz, 2010). Spelling problems have been associated with deficits in phonological awareness (PA) at least at the beginning of literacy instruction.

Phonological awareness is essential for the first stage in spelling development, as spoken words have to be separated into their phonological units in order to be translated into the corresponding letters (graphemes). Through repeated encountering, word-specific orthographic representations are built-up and precise orthographic representations are stored in long-term memory. Precise orthographic representations are a prerequisite of orthographically correct spelling, as breaking down the dictated word in its constituting sounds results in phonologically correct but orthographically incorrect spellings (e.g., [ʁaɪ̯n] might be spelled rane instead of rain). Deficits in storing precise word-specific representations in memory have been suggested to represent the main problem associated with spelling disorder (Mehlhase et al., 2018). However, these imprecise representations seem to be sufficient for recognizing a word during reading (Frith, 1985; Gangl et al., 2018), explaining why a number of children experience spelling problems in the context of adequate reading skills.

With respect to reading, word recognition theories (e.g. Coltheart et al., 1993; Perfetti and Hart, 2002; Share, 1995) imply that storing word-specific representations in memory is not only crucial for accurate spelling but also a premise of fluent reading. If a word form is stored in memory, the reader can access the whole word in a fast and automatic way instead of decoding it letter-by-letter. However, it has recently been shown, that building-up word-specific orthographic representations does not automatically guarantee fluent word reading. In addition, the speed of accessing these word-specific representations (visual-verbal access) and the time required for processing words are also crucial factors of reading fluency (Bakos et al., 2018). Visual-verbal access and efficient processing is also required in rapid automatized naming tasks (RAN tasks), where individuals are asked to name a matrix of visually presented items (colours, objects, letters, or digits) as fast as possible (Denckla and Rudel, 1976). RAN tasks usually consist of 5 different items repeated several times, so that semantic and conceptual processing requirements are reduced. Therefore, individual differences in rapid naming tasks are likely to reflect the speed of visual-verbal access and the efficiency of processing. This is especially the case in alphanumeric RAN-tasks (letters and digits), as letters and digits are more automatized than non-alphanumeric stimuli (pictures and colours) (for a review see Kirby et al., 2010). Furthermore, it has been suggested that the sequential format of the standard RAN task (several items presented row-wise) also plays a role in explaining the association between RAN and reading fluency. However, it should be noted that reading fluency is also associated with discrete RAN formats (where items are presented one-by-one) and individuals with RD show deficits in both serial and discrete RAN (although more pronounced when presented in serial RAN formats). Thus, serial RAN is more strongly associated with reading because it contains one more cognitive factor, which is important for fluent reading, namely the pre-processing of the subsequent word/item during sequential processing. However, as the implementation of a serial RAN task in combination with ERP measurements poses severe difficulties, we focused on access speed and processing duration of single items, which can be well measured in a discrete naming task with repeated stimuli.

Taken together, the RAN task (as well as discrete naming speed tasks; Gasperini et al., 2014) has been repeatedly shown to be one of the strongest predictors of reading fluency. Reading disorders are thus strongly associated with poor performance in RAN tasks (e.g., González-Garrido et al., 2011; Moll and Landerl, 2009; Wimmer and Mayringer, 2002). However, the exact nature of naming deficits in RD is still not sufficiently understood yet. For example it is still unanswered, whether the naming delay measured on the behavioural level is caused by delayed access, meaning that visual-verbal access and word processing starts later or whether it is caused by prolonged visual-verbal access and processing. Neurophysiological (e.g. event-related potential; ERP) measurements can give insight into the exact time course of the naming process and could therefore allow to identify at which time point and in which neurobiological process differences between typically developing (TD) children and children with reading disorders arise. Such findings could have implications for diagnosis and treatment of reading disorders. At the current state, reading fluency seems hard to train, given that previous intervention studies have shown only small training effects and low transfer to unlearned word material (Huemer et al., 2008; Thaler et al., 2004). A better understanding of the automatization deficit associated with naming speed delays might help to develop interventions that are more specific and thus more effective (Galuschka et al., 2014).

Furthermore, neurophysiological investigations of naming processes could inform whether naming processes are indeed unimpaired in children with specific spelling disorders. Behavioural data suggest that performance on naming speed tasks is comparable between children with spelling disorder and TD children. However, behavioural measures can only inform about the outcome, but not about the process itself. It is possible that children with spelling disorders rely on different processes during naming as TD children (e.g. more efficient visual processing) in order to compensate for their phonological and orthographic difficulties.

For this reason, we implemented a delayed digit naming ERP-paradigm with repeated stimuli in a group of TD children (with age-appropriate reading and spelling skills), a group of children with reading deficits (further called RD; corresponding to the ICD-10 diagnosis category F81.0), and a group of children with isolated spelling deficits who did not have reading difficulties (further called iSD; ICD-10 diagnosis category F81.1). The delayed-naming paradigm has been applied successfully in ERP studies before and consists of the presentation of pictures, letters or digits which must be named after a short delay. Importantly, it has been shown that the delayed naming paradigm results in event-related potential (ERP) components similar to immediate-naming tasks, at least in the first 600 ms (Laganaro and Perret, 2011). As lexical processing of the stimuli takes place approximately between 280 and 500 ms after stimulus presentation in children (Laganaro et al., 2015), the delayed naming paradigm provides a time window that is long enough to examine the naming process of interest. Furthermore, the implementation of a delayed-naming paradigm in combination with neurophysiological measurements has the advantage over immediate naming that fewer trials need to be excluded due to movement artifacts. This allows shortening testing times and thus increases compliance in primary school aged populations.

In the current study, we applied a digit naming task as the majority of investigations found that alphanumeric stimuli (letters and digits) are more automatized and more strongly related to reading fluency deficits than non-alphanumeric stimuli (pictures and colours; for a review see Kirby et al., 2010). We used digit naming because performance in letter naming is confounded by reading experience. In order to use a similar task to the standard RAN-digit paradigm normally used in behavioural studies (Denckla and Rudel, 1976), we presented only eight different single-digits, repeated over time.

With respect to the naming process itself, behavioural, modelling and electrophysiological studies identified a minimum of three main mental operations required (for reviews see Indefrey, 2011; Wolf et al., 2000): In the first step, the presented item is visually analysed. Visual recognition of the item is followed by a lexical process including semantic and phonological access and retrieval of the word (in this case the digit name) in the mental orthographic lexicon. The last step is motor planning (preparation of articulation). To estimate the temporal sequence of these processes, we rely on picture and letter naming studies, as digit naming has not yet been combined with ERPs. We assume however, that the temporal frame of the ERPs is comparable for different formats of naming tasks (letter, digit or picture naming tasks), as the sequence and timing of the ERP components elicited in response to alphanumeric and non-alphanumeric stimuli has been found to be similar (Cohen et al., 2018). Furthermore, functional resonance imaging studies have shown, that all naming tasks (letter-, digit- and object naming) result in a left-dominant neural activation of reading related neural circuits (including the left inferior temporal lobe, left motor cortex, left superior parietal gyri, and medial SMA cortex), even though letter- and digit-naming tasks lead to greater activation in semantic and articulatory regions than picture naming tasks (Cummine et al., 2014). Based on these findings, the following temporal frame for the ERP components have been expected (Cohen et al., 2018; Laganaro and Perret, 2011; Laganaro et al., 2012; 2015): Pre-lexical (visual) processes are expected to take place before the first 280–300 ms, reflected in a P1-N1 complex over occipito-temporal areas, whereas lexical processes are expected to start after the first 280 ms in 10–12 year old children (P2/N2 complex).

The above described components might be different in individuals with reading disorder compared to TD children, although findings in this domain are still very scarce and inconclusive (Cohen et al., 2018; Greenham et al., 2003; Trauzettel-Klosinski et al., 2006), especially with respect to automatized naming processes. Existing studies have mainly used picture naming tasks with different stimuli rather than a restricted set of stimuli. In contrast to a repeated stimulus presentation the use of different stimuli is not well suited to capture automatization.

The research questions of the present investigation are thus as follows:

1. Are the neurophysiological processes underlying repeated digit naming different in children with RD compared to TD children? If yes, at which processing step do these differences emerge? Are the differences associated with delayed or with prolonged processing?

In TD children, we hypothesize similar neurophysiological naming processes as reported by Laganaro et al. (2015) and Cohen et al. (2018). More specifically, we expect to find a P1-N1/N2-P2 complex distributed over occipito-temporal sites in the TD group, reflecting visual and lexical selection processes. In the RD group however, we expect to find a different neurophysiological pattern. Lexical processing steps (starting after the first 280–300 ms, reflected in the P2/N2 complex) might start later (delayed start of processing) or take longer (prolonged processing) in this group, which would provide an explanation for longer naming and reading times observed in behavioural studies. Importantly, we do not expect to find any differences between the TD and RD groups in early visual processing of the stimuli (e.g. in the first 280 ms). Evidence for visual deficits in dyslexia, such as a magnocellular deficit (Stein, 2014; Stein and Walsh, 1997) or a visual attention deficit in dyslexia (Facoetti and Turatto, 2000) based on behavioural data is still controversial (see Wimmer and Schurz, 2010). Previous neurophysiological studies found differences between good and poor readers with respect to the N2/P2 components only but did not find evidence for visual impairments during early stages of visual processing (Bakos et al., 2017; Cohen et al., 2018). Based on these findings we do not expect to find group differences in early visual processing stages.

2. Do neurophysiological processes underlying digit naming differ between children with iSD and TD children?

Behavioral findings suggest that children with iSD are not impaired in naming speed (Moll and Landerl, 2009; Wimmer and Mayringer, 2002). However, it is unclear whether the same processes are used in children with iSD compared to TD children. Thus, we will test this question without a directed hypothesis in an exploratory analysis.

2. Method

2.1. Ethics statement

The study was approved by the institutional review board of the 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 study and gave their written consent. Children received vouchers in return for their participation.

2.2. Participants

The current study was part of a large project investigating dissociations between reading and spelling disorders. Children were tested at two time-points, at the end of grade 3 (T1; ~ 9 years old) and one year later at the end of grade 4 (T2 ~ 10 years old). To initially identify children with reading or spelling disorders at T1, standardized classroom tests of sentence reading fluency (Wimmer and Mayringer, 2014) and spelling (Müller, 2004) were used. A reading or spelling deficit was defined by scores at or below the 20th percentile, age-adequate performance by scores between the 25th and 75th percentile. Following the screening, children were also individually administered a standardized one-minute word and pseudoword reading speed test (Moll and Landerl, 2013). One year later at T2, reading and spelling was re-assessed individually, using a standardized spelling test (Stock and Schneider, 2008) and the standardized one-minute word and pseudoword reading speed test (Moll and Landerl, 2013) that was already applied at T1.

The paradigm reported here was conducted at T2. Children were included in the reading deficit (RD) group, if they performed at or below the 20th percentile in at least one of the two actual reading tests at T2. In addition, the reading score averaged across all four reading tests (word and pseudoword reading at T1 and T2) had to be at or below the 25th percentile. Children were included in the spelling deficit (iSD) group if they performed at or below the 20th percentile in the spelling test administered at T2 and if their spelling score averaged across the two spelling tests

(at T1 and T2) were at or below the 25th percentile. Furthermore, children in the iSD group had to score above the 25th percentile on at least one of the reading subtests at T2 and had to have a mean reading score (T1 and T2) above the 25th percentile. This procedure ensured that literacy deficits were persistent. Children were assigned to the TD group if they scored above the 25th percentile on at least one of the actual reading subtests and on the spelling test at T2. Furthermore, the mean reading and spelling score (T1 and T2) had to be above the 25th percentile in order to be included in the TD group. To exclude children with untypically high reading and spelling scores, only children with reading or spelling scores under the 85th percentile at T2 were included in the analysis.

Although these strict selection criteria (several measurement time points, several literacy measures) resulted in a relatively small iSD sample, the procedure ensured that the literacy deficit profiles of the examined groups were persistent. And even though the cut-off criterion at T2 was rather lenient (<20th percentile), all children with a reading or spelling disorder included in the study fulfilled diagnostic criteria for either F81.0 or F81.1 (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). Additional inclusion criteria were a nonverbal IQ $\geq$ 85, German as first language, normal or corrected-to-normal vision, absence of neurological deficits and no symptoms of AD(H)D as measured by a standardized parental questionnaire at T1 (DISYPS-II; Döpfner et al., 2008).

Ninety-one children (29 TD children, 48 children with RD and 14 children with iSD) fulfilled the criteria described above. During further processing, we excluded 2 children (1 TD child and 1 child with RD) based on incomplete ERP data and 3 children (2 children with RD and 1 child with iSD) based on ERP quality (see also "ERP acquisition and pre-processing").

The final sample included 86 children: 28 TD children, 45 children with RD and 13 children with iSD (see Table 1). There were no significant differences between the groups in intelligence, gender or handedness (all *ps* > 0.23). Although all children were in grade 4, the iSD group was three to four months older than the RD and the TD group (*ps* < 0.05). In line with our selection criteria, the groups differed in their actual reading speed and spelling performance (see Table 1). Post-hoc tests revealed that children in the TD and iSD groups read significantly faster than children in the RD group (all *ps* < 0.001). There was no difference between the TD and iSD group in reading speed for words and pseudowords (both *ps* > 0.41). With respect to spelling performance, the TD group outperformed both the RD and iSD group (both *ps* < 0.001) but the RD group had higher spelling scores than the iSD group ($p < .05$). This is due to the fact that not all children in the RD group (28 out of the 45) had spelling problems in addition to readings problems. RAN deficits were only evident in the RD group. Children in the RD group named fewer items per second correctly than children in the iSD or TD group (both *ps* < 0.01), while there was no difference between the TD and iSD group in RAN performance ($p = .42$).

2.3. Background cognitive measures

2.3.1. Literacy

2.3.1.1. Reading. A standardized reading speed test (Wimmer and Mayringer, 2014; parallel-test reliability between $r = 0.95$ and 0.87 and content validity $r = 0.89$ and 0.55 for grades 2 to 8 according to manual) was used for screening in classroom settings at the end of grade 3 (T1). Children read simple sentences silently and marked them as semantically correct or incorrect (e.g., "Trees can speak."). After three minutes, the task was terminated and the number of correctly marked sentences was scored. In addition, an individually administered one-minute reading fluency test (Moll and Landerl, 2013; parallel-test reliability $r = 0.90–0.94$ and content validity $r = 0.69–0.85$) was administered at the end of grade 3 (T1) and grade 4 (T2). The test contains a word and pseudoword reading list with items increasing in length and complexity. The task of the child is 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 within the one-minute time limit.

2.3.1.2. Spelling. Spelling was assessed twice, at the end of grade 3 (T1) and grade 4 (T2). Given that all German spelling tests are grade specific, two different tests had to be used. The standardized spelling test administered in grade 3 (Müller, 2004; parallel-test reliability $r = 0.92$ and content validity $r = 0.78$) consists of 44 single words, which have to be written into sentence frames. In the standardized spelling test administered in grade 4 (Stock and Schneider, 2008; parallel-test reliability $r = 0.95$ and content validity $r = 0.79$) children were asked to write 10 sentences (92 words), which were dictated by the examiner. The number of misspelled words was scored.

2.3.2. General cognitive ability

The German version of the Culture Fair Intelligence Test (CFT-20-R; Weiß, 2006) was administered at the end of grade 3 (T1). The CFT-20-R is designed to estimate nonverbal IQ without the influence of sociocultural and environmental factors. It comprises 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 $r = 0.78–0.83$).

Table 1
Descriptive statistics of the groups and between group comparisons. Standard deviations are reported in brackets. Subscript digits indicate that the mean differs significantly ($p < .05$) from the referred-to mean: 1 = TD, 2 = RD, 3 = iSD.

	TD group (N = 28)	RD group (N = 45)	iSD group (N = 13)
Age in month	122.9 (4.7) $_{3}$	123.7 (5.2) $_{3}$	127.0 (6.5) $_{12}$
IQ	109.4 (11.4)	111.2 (13.3)	108.3 (10.9)
Handedness[a] (left/right)	6/22	6/39	1/12
Gender (females/males)	12/16	25/20	4/9
T2: spelling[b]	58.6 (11.9) $_{23}$	21.0 (19.4) $_{13}$	9.9 (4.4) $_{12}$
T2: reading words[b]	54.7 (15.5) $_{2}$	13.3 (9.5) $_{13}$	51.1 (17.5) $_{2}$
T2: reading pseudowords[b]	50.6 (20.6) $_{2}$	13.5 (7.4) $_{13}$	47.8 (19.9) $_{2}$
RAN-digits[c]	2.21 (0.45) $_{2}$	1.88 (0.35) $_{13}$	2.32 (0.38) $_{2}$

[a] Self-report
[b] Percentile ranks
[c] Correct items per second.

2.3.3. Rapid automatized naming

We presented a standard RAN-digits paradigm (e.g. Denckla and Rudel, 1976) at T2. Children had to name 40 digits presented in eight lines and five columns as quickly and accurately as possible. Each item (the digit 2, 3, 5, 8 or 9) was presented only once in each line in a randomized order. We recorded the time needed to name the full item set and marked any occurring errors. For the analysis, we computed the number of correctly named items per second.

2.4. Stimuli and procedure

During ERP measurement at T2, children performed a delayed naming task. The task of the child was to name the visually presented digit at the request sign (question mark). The examiner judged the naming performance of the child by button press. The naming was judged as correct if the item was named correctly and if the child named the item at the requested time point. Naming before the request sign was judged as incorrect. There was a total amount of 40 stimuli presented, including eight different monosyllabic digits (1, 2, 3, 4, 5, 6, 8 and 9) repeated five times.

The 40 stimuli were presented intermixed in two pseudorandomized lists. The pseudo-randomization ensured that digits were equally distributed across the experiment and that there were no "n-1" and "n-2" repetitions of the same digit. The two versions were assigned randomly to the participants within each group. Total presentation time was about 4–5 minutes depending on the response times of the participant. Before the start of the experiment, participants were introduced to the 8 numbers and a practice block consisting of 8 trials (presentation of each digit once) was completed. The practice block familiarized the participants with the visual characteristics of the stimuli and the sequence and requirements of the experiment (i.e. the delayed naming at the requested time point).

The experiment was presented on a high resolution (1920 × 1080) 24-inch monitor (60 Hz refresh rate) using E-Prime® 2.0 software (Psychology Software Tools, Inc). All stimuli were presented in black on white background. Each experimental trial started with a fixation cross presented for 1000 ms in the middle of the screen, which signalled the position of the upcoming digit stimulus. Digits were presented in Point Size 68 (Font: Arial) for 700 ms, which with a viewing distance of 70 cm resulted in a vertical visual angle of 1.45° and in a horizontal visual angle of 0.96°. The presentation time of 700 ms corresponds to naming latencies in children in single word production tasks (Cohen et al., 2018; Gasperini et al., 2014; Laganaro et al., 2015). After a jittered interval (500–1000 ms; blank screen), a question mark presented on the middle of the screen signalled for naming. The next trial started after the button-press of the examiner (see Fig. 1).

2.5. ERP acquisition and pre-processing

Continuous electroencephalogram (EEG) was recorded with an Electrical Geodesics Inc. (Eugene, OR) 128-channel system during testing (HydroCel Geodesic Sensor Net HCGSN; sampling rate: 500 Hz, reference: Cz). Impedance was monitored and kept below 50 kΩ throughout the recording. The pre-processing was performed with BrainVision Analyzer 2.0 (Brain Products GmbH, Gilching, Germany).

During pre-processing, the ERP-signal was first visually inspected in order to detect and exclude large artefacts, which might have negatively influenced further processing steps. Then, 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

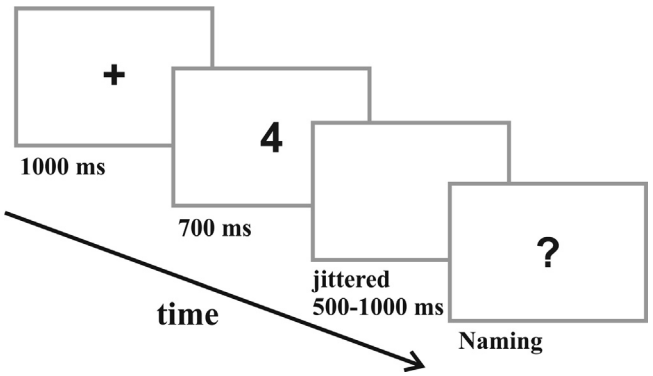

Fig. 1. An example trial of the delayed digit naming task. Participants were instructed to name the presented digit at the request sign (question mark). The examiner rated the naming as correct or incorrect.

algorithm, total squared correlations to delete: 30%; Gratton et al., 1983; Plank, 2013). Other artefacts 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). The ERPs were re-referenced to the average of all electrodes.

Next, the continuous data was segmented into epochs from −200 ms to 1000 ms relative to stimulus onset, with the 200 ms pre-stimulus interval serving for baseline correction. The length of the time window was selected based on the literature, showing picture naming latencies of approximately 900–1000 ms and letter or digit naming latencies of approximately 700 ms in children (Cohen et al., 2018; Gasperini et al., 2014; Laganaro et al., 2015). Individual segments were averaged separately for each participant over each electrode. In order to be included in the analysis, averages had to be based on more than 15 artefact-free trials. Electrodes with less than 15 artefact-free trials were set missing. Furthermore, participants were excluded completely if there were more than 5 channels with less than 15 artefact-free trials in their data (see also Participants section) or more than 2 channels were missing from a region of interest (ROI; see below). Only correct answer trials were analysed. The average number of accepted trials was (M [SD] by a max. of 40 items) 36.8 [2.43], 36.5 [2.95] and 35.8 [4.35] for the TD, RD and iSD group, respectively. There was no significant difference between the groups in the number of accepted trials (all *ps* > 0.31).

2.6. Statistical analysis – RD vs. TD

2.6.1. ERP waveform analysis

We compared the individually averaged ERP waveforms of the RD and TD groups via unpaired t-tests at each electrode and time point (every 2 ms) during the first 600 ms in order to detect time periods of significant group differences. We retained differences only if they were significant over at least 20 milliseconds and 3 adjacent electrodes at an alpha criterion of 0.01. These analyses were carried out in CARTOOL software (Brunet et al., 2011) and plotted using MATLAB R2015a.

ERP waveforms were additionally characterized and analysed with respect to the components P1 and N1 in an occipital region of interest (electrodes 70, 71, 74, 75, 76, 82 and 83; marked red in Fig. 2) and the P2 in bilateral occipito-temporal regions of interest (electrodes 52, 58, 59, 60, 64, 65 and 66 and electrodes 84, 85, 90, 91, 92, 95 and 96, respectively; marked blue in Fig. 2). We searched for the peak amplitudes of the P1, N1 and P2 components

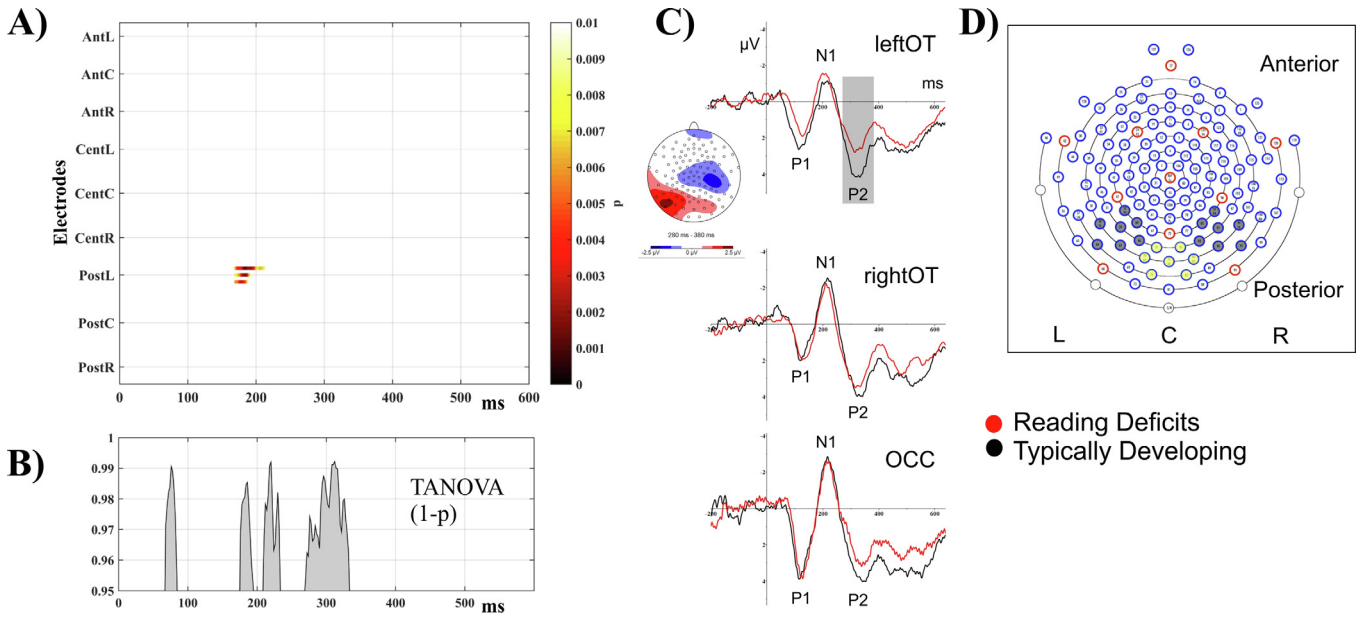

Fig. 2. **(A)** Significant differences between the TD and RD groups on the ERP amplitudes on each electrode (Y axes) and time point (X axes) and **(B)** the results of TANOVA (1-p values). **(C)** Illustration of the grand-average ERP waveforms depicted separately for the groups over an example electrode of the left occipito-temporal (leftOT), the right occipito-temporal (rightOT) and the occipital ROI (OCC). The time window of significant group difference is laid over with a gray bar and illustrated by the topographic distribution of the difference wave (TD minus RD group). Negativity is depicted upwards. **(D)** An illustration of the Geodesic Sensor Net; Electrodes included in the OCC (P1, N1) are filled in yellow; electrodes of the leftOT and rightOT (P2) are filled in gray. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between 90–160 ms, 170–250 ms and 280–380 ms, respectively. Amplitudes were then compared between the TD and RD groups with Welch's t-test by an alpha level of 0.05. Welch's t-test has been shown to be more robust in case of unequal sample sizes than the more widely used Student's t-test (Moser and Stevens, 1992; Ruxton, 2006).

Furthermore, in order to examine the effect of repetitions on the ERPs, the components (P1, N1, and left and right P2) were additionally compared between the first half of the trials (trials 1 to 20) and the second half of the trials (trials 21 to 40) within each group (within-samples t-tests; alpha level of 0.05). The application of the same criteria as described above (e.g. a minimum of 15 artefact-free trials per electrode; no more than 2 excluded electrodes per ROI) reduced the sample size to N = 22 for the TD and to N = 38 for the RD. The average number of accepted trials was in this case (M [SD] by a max. of 20 items) 18.7 [0.89] and 18.4 [1.09] for the first half of the trials and 19.1 [0.70] and 18.9 [0.82] for the second half of the trials (TD and RD group, respectively). There were no significant differences between the groups in the number of accepted trials (both *ps* > 0.45).

2.6.2. Exploratory ERP waveform analysis

In case of significant group differences, we further explored the relationship between performance on the behavioural RAN-task and the neurophysiological measurements by computing Pearson's correlation coefficient (two-sided; alpha level of 0.05) between the amplitude of the respective ERP component and the RAN task (items named per second).

2.6.3. Global topographic pattern analysis (spatio-temporal segmentation)

Waveform analyses provide first information about whether and at which time point group differences occur. The global topographic pattern analysis can extend these findings by providing information about whether group differences are due to modulations in the timing and strength of the activation or reflect different underlying neurophysiological processes.

First, a "topographic ANOVA" (TANOVA; Murray et al., 2008) as implemented in CARTOOL software (Brunet et al., 2011) was run over all electrodes and over the first 600 ms at a conservative alpha criterion of 0.01, in order to identify periods of significant topographic differences between the two groups. Next, we performed a spatio-temporal segmentation on the group-averaged ERP waveforms to reveal topographic differences between the groups. While the TANOVA tells us whether there are topographic differences between the groups, the spatio-temporal segmentation delivers further information about the affected processes. The spatio-temporal analysis summarizes the ERP data into a certain number of topographic maps (Brunet et al., 2011), corresponding to different underlying cognitive processes. As the start (onset latency) and end point (offset latency) of these stable topographic maps can be determined, the spatio-temporal segmentations can help to disentangle the question whether a delay is caused by a later onset of a process or by a prolonged processing. For this purpose we used a modified hierarchical clustering analysis (Michel et al., 2001; Pascual-Marqui et al., 1995), namely the agglomerative hierarchical clustering (Murray et al., 2008) as implemented in the CARTOOL software (Brunet et al., 2011) and determined the optimal number of maps based on the Krzanowski-Lai criterion (Murray et al., 2008; Tibshirani and Walther, 2005). Statistical smoothing was used in order to exclude maps with low strength (Murray et al., 2008; Pascual-Marqui et al., 1995). Furthermore, maps were merged together if they correlated above 95% and were rejected if they were present for less than 20 ms.

Finally, the pattern of map templates observed in the group averaged ERPs was compared to each individual subjects' ERP. This is called "microstate fitting" in CARTOOL, which describes the goodness of fit (GEV: Global Explained Variance) and the duration (i.e., the average duration that a given microstate remains stable) of each map for each participant. Furthermore, the onset and offset latency of a given template map was determined. We compared

these values between the TD and RD groups with between-samples t-tests by unequal variances. As the number of t-tests was relatively high for this analysis (4 measurements: GEV, onset, offset latency and duration * 8 microstates), we have reduced the alpha level to 0.0016 (0.05/32) based on the Bonferroni correction method.

2.7. Statistical analysis – iSD vs. TD

The relatively small sample size of the iSD group allowed us to conduct only preliminary, exploratory analyses. Thus, for this group, we conducted only peak amplitude comparisons via between sample t-tests (as described above).

3. Results

3.1. Behavioural results

Naming accuracy was very high in all groups; 96.8% in the TD group, 95.8% in the RD group and 93.7% in the iSD group. There was no difference in naming accuracy neither between the TD and the RD group (p = .37), nor between the TD and the iSD group (p = .30).

3.2. ERP results

3.2.1. TD-RD comparison

3.2.1.1. ERP waveform analysis. Fig. 2 illustrates significant ERP waveform differences between the groups. Peak analyses showed a significant difference in P2 (280–380 ms) amplitudes in a left parieto-temporal region; $t(50.42)$ = -2.38, p = .02, d = 0.57; P2 amplitudes were higher (more positive) in the TD group than in the RD group (see Table 2 and Fig. 2). There were no differences between the amplitudes of the TD and RD groups in other ERP components (occ. P1, occ. N1, and P2 over right hemisphere; all ps > 0.50).

The comparison of the first and second half of the trials revealed no effect of repetition in the RD group. Amplitudes were comparable over time in all components and ROIs (all ps > 0.18). However, repetition had a significant effect on P2 amplitudes in the right hemisphere of the TD group; $t(21) = -2.47$, p = .02 d_z = 0.53; P2 amplitudes were reduced in the second half of the trials compared to the first half of the trials (see Fig. 3). There were no other significant differences with respect to repetition effects in the TD or RD groups (all other ps > 0.18).

3.2.1.2. Exploratory ERP waveform analysis. Furthermore, we have found a positive correlation between the left hemispheric P2 amplitude and RAN task performance; $r(73)$ = 0.24, p = .04; suggesting better performance on the RAN task for higher P2 amplitudes.

3.2.1.3. Global topographic pattern analysis. As presented in Fig. 4, spatio-temporal segmentation applied on the group-averaged data revealed ten stable topographic maps, which accounted for 91.2% of the variance. The maps 1–8 were fitted to the individual ERPs in a time window from 0 to 600 ms. As map 9 and 10 might have reached beyond the analysed 600 ms long time window, these maps were excluded from further analyses. TANOVA indicated different topographic patterns between the TD and RD groups in a time window of approximately 310–330 ms and for a short period of time after 200 ms (ps < 0.01; see Fig. 2).

There were no differences between the TD and RD groups in Global Explained Variance (GEV), in duration and in onset and offset latency of "map1" (all ps > 0.03), "map2" (all ps > 0.09), "map3" (all ps > 0.04), "map4" (all ps > 0.35), "map5" (all ps > 0.01), "map7" (all ps > 0.09) and "map8" (all ps > 0.20; see Fig. 4). However, there were significant differences between the TD and RD groups in presence of "map6" (see Fig. 4). "Map 6" lasted longer in children with RD (67.2 ms) than in TD children (25.6 ms); $t(60.17)$ = 3.67, p = .001, d = 0.95. GEV, onset and offset latency of "map 6" did not differ between TD and RD children (all ps > 0.07).

3.2.2. Exploratory TD-iSD comparison

There were no significant differences between the TD and iSD groups in peak amplitude measurements (all ps > 0.11).[1] For an illustration of the grand average waveforms of the iSD group, see Supplementary Material 1.

4. Discussion

We aimed to investigate the underlying neurophysiology of naming speed differences between children with reading or spelling disorders and typically developing children. Differences between TD children and children with RD emerged around 300 ms after stimulus presentation. The topographic pattern of a slightly more right lateralized posterior positivity ("map 6") started at the same time but lasted longer in the RD group compared to the TD group. Similarly, left hemispheric P2 amplitudes (280–380 ms) were smaller in the RD than in the TD group. In contrast, we found no neurophysiological differences between TD children and children with iSD. In the following, we discuss the implications of these finding separately for the two group comparisons.

4.1. TD-RD comparison

As expected, we found a P1-N1 complex, extending over occipital surfaces, represented by "map 3" and "map 5" (see Fig. 2 and Fig. 4). These components have been discussed to reflect visual processes, which can extend up to 280 ms in 10–12-year-old children and are likely to originate from the bilateral occipital lobe (Cohen et al., 2018; Laganaro et al., 2015). There were no group differences in the waveforms and topographic patterns of these early processes. Thus, naming speed delays in reading disorders are unlikely to originate from early visual processing difficulties (P1/N1 components). This is in line with previous studies, showing intact visual processing in dyslexia (e.g. Bakos et al., 2017; Cohen et al., 2018; Wimmer and Schurz, 2010; but see also Facoetti and Turatto, 2000; Stein, 2014; Stein and Walsh, 1997).

Consistent with previous studies, we found bilateral temporo-parietal positivity starting to emerge after 280 ms, represented in the P2 component. At approximately 300 ms after stimulus presentation, ERP patterns started to differ between TD children and children with RD, which is similar to previous findings (Cohen et al., 2018): Extending previous findings, we could show that this difference is due to a prolonged duration of "map 6" - a slightly right lateralized posterior positivity - in the RD group. Correspondingly, P2 amplitudes were less positive over the left hemisphere in the RD group, compared to the TD group. As left inferior parietal regions (as well as the inferior temporal lobe and the left posterior occipitotemporal sulcus) and the P2 component are related to the recall

[1] Considering only the actual measurement time point, when the neurophysiological assessment was conducted (T2), and including children in the iSD group if they scored at or above the 25th percentile on a reading test and under the 20th percentile on the spelling test at T2 irrespective of the previous measurement time point (T1), the sample size of the iSD group increased to 16 children. However, re-running the analyses based on the larger sample did not change the results. Again, we did not find any significant differences in amplitude size between the control and the iSD group (all ps > 0.13).

Table 2
Mean amplitudes (standard deviations) of the measured event-related potential components averaged over the electrodes of the respective ROI and reported in μV. *P*-values are reported for the comparison to the TD group.

	TD group (N = 28)	RD group (N = 45)	*p*-values	iSD group (N = 13)	*p*-values
P1	4.93 (3.42)	5.00 (3.35)	0.93	5.28 (3.48)	0.76
N1	−3.55 (3.67)	−3.67 (3.41)	0.88	−3.31 (2.54)	0.84
P2 - left	4.62 (2.70)	3.21 (2.29)	0.02	3.28 (2.37)	0.11
P2 - right	5.61 (2.84)	5.11 (3.51)	0.52	6.13 (2.72)	0.59

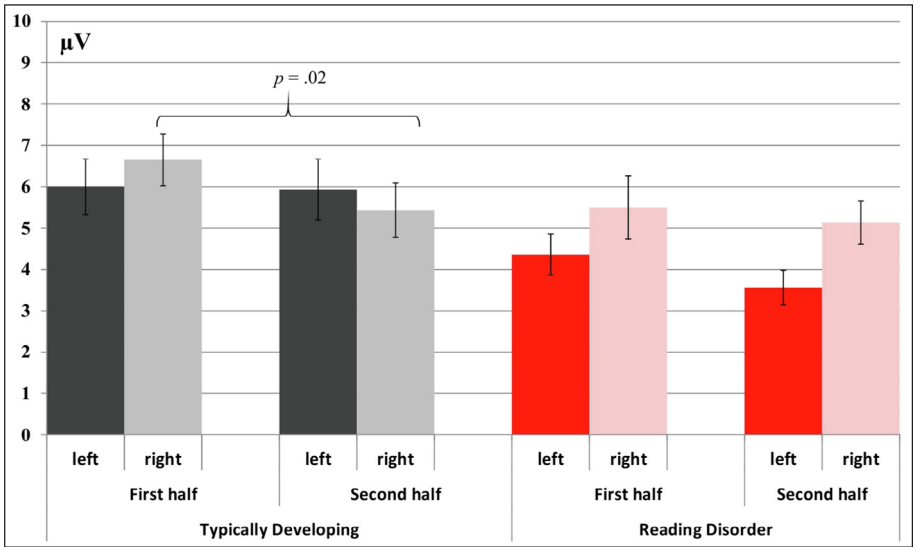

Fig. 3. P2 amplitudes, reported separately for the first and second half of the trials. Mean values (in μV) depicted separately for the two regions (left vs. right hemisphere), the experimental halves (first vs. second half of the experiment) and the two groups. Bars represent the standard error of mean. Significant differences are indicated with their *p*-values above the brackets.

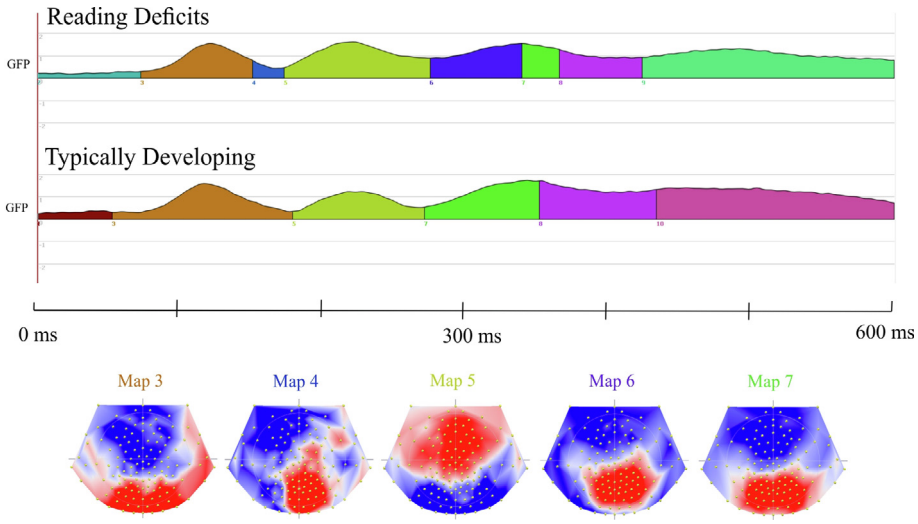

Fig. 4. Illustration of the temporal and spatial distribution of the topographic maps resulting from the spatio-temporal segmentation. Red color in the topographic maps represent positive values, blue color represents negative values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of verbally coded information (Acres et al., 2009; Gainotti, 2014) and to lexical access (Indefrey, 2011; Laganaro et al., 2015; Mano et al., 2013), it can be argued that the hemispheric difference (less activation in the left hemisphere compared to the right hemisphere) in the RD group reflects problems in the mapping of visual stimuli to phonological representations (visual-verbal access). The longer duration of "map 6" in RD with an otherwise typical onset time indicates that phonological / verbal processing in children with RD starts at the same time as in TD children, but takes longer. This finding is in line with findings from Bakos et al. (2018), showing similar results in a phonological lexical decision task. Processing of visually presented words took longer in children with RD

compared to TD children. Based on these findings, we assume that slow reading, as well as difficulties in RAN tasks in RD might be a result of prolonged visual-verbal processing.

A further important finding is a right-hemispheric P2 amplitude height reduction over trial repetitions in TD children. This reduction is generally interpreted as a habituation effect, reflecting that children got more acquainted with the characteristics of the stimuli during the experiment. In contrast, children with RD did not show any neurophysiological effects with respect to stimulus repetition. We assume that children with RD used a different strategy during naming compared to TD children. While TD children probably related the visual characteristics of the stimuli to the corresponding phonological representations (visual-verbal access), children with RD might have relied stronger on the visual characteristics of the stimuli only. This interpretation is supported by the fact that the right hemisphere, especially the right inferior and right anterior temporal lobe, has been related to processing of visual information (Acres et al., 2009; Gainotti, 2014). Based on these findings, the habituation effect in the right hemisphere is likely to reflect facilitated visual processing in TD children, resulting from a stronger reliance on the phonological (verbal) feature of the stimuli, processed in the left hemisphere. In contrast, children with RD did not benefit from the phonological feature of the digit name. As a consequence they needed to rely more on visual processing of the stimuli. This is in line with other findings, showing reduced neural habituation to repeated visual stimuli in poor readers and in children at family risk of dyslexia (Regtvoort et al., 2006).

4.2. TD-iSD comparison

There were no differences between the TD and iSD groups in the underlying neurophysiology of naming processes. This is in line with behavioural findings (e.g. Moll and Landerl, 2009) showing that naming speed deficits are only related to reading but not to spelling problems. Thus, visual-verbal access and processing seems to be intact in children with iSD (Bakos et al., 2018; Gangl et al., 2018; Moll and Landerl, 2009; Perfetti and Hart, 2002). However, these findings result from exploratory analysis only, thus, further studies are needed in order to confirm these findings.

4.3. Limitations and future research

The current sample was very homogenous in grade level. A homogenous sample has the advantage of greater statistical power; however, it reduces the generalizability of the findings. In studying developmental disorders, it is especially important to consider age-related changes. It might be possible that children with reading disorders are only protracted but not permanently affected in their development, and thus would show similar neurophysiological patterns as younger TD children. This question might be well addressed by future research comparing the RD-group with a reading-level-matched control group in addition to the age-matched control group.

Furthermore, we have to note that the sample size of the iSD group was relatively small (n = 13) compared to the sample size of the TD (n = 28) and RD groups (n = 45). Our findings about isolated spelling disorders thus only provide first insights about the neurophysiological naming processes of this group and have to be interpreted with caution until the results are replicated in a larger sample.

Further limitations include methodological considerations. In order to avoid motor artefacts, we have implemented a delayed naming paradigm instead of measuring immediate naming. Even though it has been shown that delayed naming results in similar ERP components than immediate-naming (Laganaro and Perret, 2011) this was not directly tested in the current study. Finally, the assessment of trial repetition effects is based on a set of only 20 trials. Future investigations should repeat the experiment with a larger trial number, in order to confirm our findings.

Author contributions

KL, GSK and KM were involved in the conception and design of the study. SB, HM and KM developed the methods. SB, HM and KM acquired the data. SB and JB 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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Declaration of Competing Interest

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.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clinph.2019.11.017.

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