Mode effect: An issue of perspective? Writing mode differences in a spelling assessment in German children with and without developmental dyslexia

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Full title:

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Short title:

Writing mode differences

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Abstract:

Digital technology has an increasing influence on writing processes. In this context, the question arises whether changes in writing mode (i.e., handwriting vs. computer-keyboard typing) also require changes in writing assessments. However, data directly comparing writing mode influences in children with and without developmental writing deficits are scarce.

This study investigated the influence of writing mode in German-speaking, typically developing children and children with developmental dyslexia (DD) from two different levels. Results showed on a general level that writing mode influenced overall *spelling accuracy*, *writing time, and self-corrections* comparably in children with and without DD. On a rule-specific level, outcomes for writing time and self-corrections substantiated these findings. However, as regards *spelling accuracy*, a mode effect was only apparent for capitalization, whereas other spelling rules were resistant to writing mode influences.

Present findings suggest that a mode effect is present only for typing specific aspects (e.g., capitalization) rather than reflecting a general influence on orthographic principles (e.g., grapheme-phoneme assignment, morphologic principles). These mode-specific aspects seem to comparably affect the writing performance of typically developing children and children with DD. We recommend writing assessments to consider that different writing modes may influence individual spelling rules differently.

Words: 195

Introduction

The importance of digital technology has increased significantly in both (school) education and the promotion of children with special educational needs in the last decade. Several advantages of computer-based testing have driven the shift towards computer-keyboard typing in educational and therapeutic contexts. These advantages include delivering new test designs and online learning options (Davies & West, 2014) and monitoring learning trajectories (e.g., Pellegrino & Quellmalz, 2010). At the same time, this shift requires further research to understand better the respective writing mode (i.e., handwriting vs. computer keyboard typing).

Considerable research has focused on the impact of the *mode effect* (i.e., differences between handwriting and computer-keyboard typing) on general cognitive processes (e.g., working memory: Carpenter & Alloway, 2019; Longcamp et al., 2008; Longcamp, Zerbato-Poudou, & Velay, 2005; Pinet, Ziegler, & Alario, 2016; e.g., cognitive load: Prisacari & Danielson, 2017). However, only a few studies have evaluated the impact of the writing mode on writing processes in typically and atypically developing children and adults so far (e.g., Berninger et al. 2009; Bisschop et al., 2017; Feng et al., 2019; Gaskill & Marshall, 2007; Lottridge et a., 2008).

To date, most studies evaluating mode effects involved typically developing children (e.g., Feng et al., 2019; Wollscheid, Sjaastad, & Tømte, 2016). However, comparably few research exists for children with DD (e.g., Berninger et al., 2009; Berninger, et al.,2015). Existing studies predominantly focused on accuracy rates, writing times, and revisions (i.e., prevailing in the form of numbers of self-corrections) at sentence and text level. However, they have neglected writing mode influences on complementary linguistic processes related to writing/spelling (e.g., phonological awareness, morphological principles and, rule knowledge).

The present article directly compared handwriting and typing in typically developing children and children with DD. For this comparison, we used a two-step approach: in the first step, we applied a holistic analysis of writing performance (i.e., the spelling of the test word was rated as either correct or incorrect). In the second step, we applied a rule-specific in-depth analysis on the level of individual spelling rules. In the following, we first report on differences between handwriting and computer-keyboard typing observed in typically developing children. We then explore differences specific to the writing mode in children with developmental DD.

Handwriting and typing in typically developing children

Writing, as we learn it traditionally with a pen(cil) in hand on a sheet of paper, is an active and highly embodied process – "a multimodal, multileveled language skill" (Berninger et al., 2015, p.3). It requires integrating visual, graphomotor, auditory, and tactile information (Mangen & Velay, 2010; discussing haptics in writing). In the development of handwriting, the visual form of a letter (or a grapheme) is associated with the neuronal representation of the respective graphomotor program (e.g., James & Gauthier, 2006; Longcamp et al., 2003). In turn, these associations affect the recognition and storage of letters (i.e., Longcamp et al., 2008, 2005; but see Vaughn, Schumm, & Gordon, 1992). In the development of computer-keyboard typing, a spatial process of learning different locations of letters on the keyboard is required instead. This process demands divided attention between the screen and the keyboard. In contrast, handwriting requires a directed focus on the tip of the pen (Mangen & Velay, 2010). These different cognitive and motoric requirements may affect the comparability of writing performance.

Mode effect studies investigating handwriting and typing performance in typically developing children focused on writing and typing times (i.e., speed, Connelly, Gee, & Walsh, 2007; Horne et al., 2011) on various language levels (i.e., grapheme, word, or sentence level; Feng et al., 2019; Pinet et al., 2016) but rarely on writing performance in terms of spelling accuracy. Mode-effect studies also considered text production, such as the quality of essay writing and the number of self-corrections (e.g., Berninger et al., 2015; Goldberg, Russell, & Cook, 2003; Wollscheid, Sjaastad, Tømte, & Løver, 2016), with different results for different age levels: Younger children were faster and produced more extended essays by handwriting (Alves et al., 2016; Connelly et al., 2007; Wollscheid et al., 2016), but they typed more automatically on the alphabetic (or grapheme) level (Berninger et al., 2009). In particular, children older than 14 years typed faster on the computer keyboard (Horne et al., 2011; Mogey & Hartley, 2013). These results indicated that computer-keyboard typing proficiency grows with age. In terms of spelling accuracy, performance did not differ between handwriting and typing in fifth-grade children (Frahm, 2013). A similar result was reported by Russel (1999; see also Russel & Plati 2002), who evaluated the quality of essay writing of eighth-graders. However, significantly more self-corrections during typing were observed (Goldberg et al., 2003). Interestingly, these self-corrections were performed online during the typing process rather than at the end of the written passage, as usually the case with handwriting.

In sum, the study results indicated that writing mode seems to influence writing performance. However, unambiguous conclusions are not yet possible for the different age groups and the effect of writing mode in atypically developing children.

Handwriting and typing in the context of DD

Developmental dyslexia is a domain-specific learning impairment of neurobiological origin that affects the typical development of language skills (Lyon, Shaywitz, & Shaywitz, 2003). Children with DD struggle to achieve accurate or fluent word reading, poor decoding, and poor spelling (Snowling et al., 2020) that persist for at least six months (Diagnostic and Statistical Manual of Mental Disorders (DSM-V; American Psychiatric Association, 2014).

DD is associated with deficits regarding attention (e.g., Rabiner et al., 2000), rapid automatized naming (RAN, Denckla & Rudel, 1976; Landerl et al., 2013), and working memory (e.g., Brooks, Berninger, & Abbott, 2011; Fischbach et al., 2014). Attentional deficits and deficits in orienting attention to a current situation are crucial factors in developing literacy difficulties (Rabiner et al., 2000). Moreover, as assessed by RAN, lexical access and retrieval is a crucial predictor of reading performance. In turn, it is a risk factor for DD when impaired (Araújo & Faísca, 2019; for a meta-analysis). Assessment of RAN involves speeded naming of visually presented stimuli (e.g., letters, objects, numbers), either unknown or practiced before (i.e., known material). Naming speed and thus, lexical access and lexical retrieval were observed to be influenced by, among others, attention, perception, and working memory processes (Wolf et al., 2000). Regarding the latter, literature provided ample evidence that dyslexic reading and writing impairments are often associated with working memory deficits (i.e., phonological processing: Berninger et al., 2006; Pickering, 2012; executive functioning: Landerl et al., 2013). Working memory deficits impede acquiring more stable morphologic representations and storing orthography knowledge in long-term memory (Fischbach et al., 2014).

However, the symptomatology of DD is very heterogeneous. Children with DD may struggle with handwriting aspects for various reasons, such as graphomotor planning and grapheme transcription (e.g., Kandel, et al., 2017), correct spelling (e.g., for children: Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008a; Cidrim & Madeiro, 2017, for a review; for adults: Coleman et al., 2009), and writing fluency (e.g., Sumner, Connelly, & Barnett, 2013; but see Martlewm, 1992). They also have difficulties recognizing and correcting errors (e.g., Horowitz-Kraus & Breznitz, 2011, for reading). These difficulties impact heavily on children's motivation to write (e.g., Berninger, Winn, et al., 2008), and thus on children's learning, self-esteem, and educational achievement (e.g., Alexander-Passe, 2006). Computer-keyboard typing may compensate for such dyslexic handwriting difficulties (Anderson, 2005), using, for example, word processing software and integrated spell checkers (MacArthur, 2009).

Printed block letters may enhance legibility and facilitate writing. However, research in this direction is scarce.

Mode-effect studies in children with DD have reported ambiguous findings for different age groups (Freeman et al., 2005; for a review): For younger children, similar results to typically developing children were observed (i.e., children were faster by handwriting, Beers et al., 2017). Morken and Helland (2013) evaluated computer-keyboard typing of ten to eleven-year-old children with and without DD in a writing-to-dictation task. Results indicated that children with DD wrote slower and less accurately but corrected their writing as typically developing children. As the study did not compare writing modes, it is difficult concluding from these results to the writing performance in handwriting. For secondary school children, opposing results were reported (Horne et al., 2011), indicating a slight advantage of computer-keyboard typing over handwriting.

Taken together, evidence as to the impact of the writing mode on the assessment of typically and atypically developing writing skills is still missing. Existing studies primarily focused on either handwriting or typing (Martlewm, 1992; Sumner et al., 2013). Studies comparing both writing modes applied between-subject designs predominantly(Lottridge et al., 2008; for a review). Thereby, they scarcely consider intra-individual mode effect differences. Intra-individual comparisons, however, are crucial for developing appropriate assessment and therapeutic approaches.

Overview of the two-step approach in the study

In the present study, we evaluated handwriting and typing skills in typically developing and dyslexic German children with DD following a two-step procedure.

In a first step, we directly compared the writing mode between children with and without DD in a combined within- and between-subject design. We used a writing-to-dictation task as it easily allows to parallelize test words to ensure comparable test conditions and avoids planning and text generation processes (Morken & Helland, 2013). We evaluated the mode effect on overall spelling accuracy, writing times, and self-corrections. Spelling performance was assessed as either correct or incorrect, as is the case in many learning assessments.

In the second step, we applied a spelling rule-specific analysis to investigate the influence of writing mode on complementary linguistic processes (e.g., phonological awareness, morphologic principles, and rule knowledge). By evaluating different spelling rules separately for each test word (i.e., capitalization, consonant doubling, lengthening, final obstruent devoicing, and rule words), we aimed at capturing processes necessary for these specific spelling rules. For instance, the realization of consonant doubling and lengthening signs requires phonological skills to monitor vowel length. Detection of final obstruent devoicing requires knowledge of morphologic principles. These spelling rules are taught in schools according to German curricula (e.g., Bildungsplan Sekundarstufe I, Ministerium für Kultus, Jugend und Sport, Baden Württemberg, 2016). We chose this approach because we expected some spelling rules to be affected differently by the applied writing mode.

We will briefly introduce the German school system and the most relevant German orthography principles for the present study.

The German school system and pedagogic approaches on orthographic principles

In Germany, the federal states are responsible for education yielding variations in the educational system. Generally, attendance at kindergarten (age 3 to 6 years) is voluntary. School attendance is compulsory from age six. A 4-year (or 6-year) primary school is the basis of the German education system. After fourth (or sixth) grade, children attend one of three secondary school tracks (two vocational and one academic track) depending on their educational achievement and parents' decision. Thereby, the German school system aims for a more homogeneous grouping of children.

When entering primary school, children already present with differences in individual learning prerequisites and learning experiences. These individual experiences are also the basis for formal instruction on orthography. German orthography is quite regular, but only for reading (i.e., from graphemes to phonemes, Wimmer & Mayringer, 2002). For writing, children need to learn many exceptions and skills. For instance, knowledge of the relatively regular phoneme-grapheme assignment (e.g., short and long vowels Stiel [ʃtiːl] vs. still [ʃtɪl] - Stahl [ʃtaːl] vs. Stall [ʃtal]) is fundamental. It has only a few exceptions (i.e., irregular words, Stil [sti:l]), which makes German orthography more consistent in contrast to, for instance, English (e.g., Landerl et al., 2013). Based on this knowledge, morphological principles are relevant to keep word forms linguistically consistent (e.g., se**h**en – du sie**h**st [Engl., to see - you see], W**a**ld - W**ä**lder [Engl., forest - forests]). Linguistic consistency is particularly relevant for the legibility of written language. Legibility is also achieved by capitalizing the most relevant words as nouns and nominalized expressions [e.g., Mit **B**ruchzahlen ist das **R**echnen schwieriger als mit ganzen **Z**ahlen (Engl., Fractions are more difficult to calculate with than integers)]. Children with DD may struggle with these necessary skills, namely with the acquisition of regular phonological and morphological principles (Snowling, 2000; Vellutino et al., 2004; for a review) as well as orthographic exceptions (Fischbach et al., 2014).

First step: Consideration at the general level

Objectives and hypotheses

Based on the previous findings, we have derived the following hypotheses: In general, we expected that both evaluation approaches (i.e., holistic vs. rule-specific approach) achieve comparable results. However, the rule-specific approach should allow a more differentiated evaluation.

For typically developing children, we expected longer writing times and more self-corrections for typing than for handwriting (Goldberg et al., 2003; Wollscheid et al., 2016). Additionally, we expected these differences to decrease with age and experience in computer usage. We did not have specific hypotheses concerning spelling accuracy because the previous studies' results were inconsistent on this point (cf. Berninger et al., 2009; Frahm, 2013).

For children with DD, we expected longer writing times and lower spelling accuracy than in the control group in both conditions (Berninger et al., 2009). We also expected younger children to be faster in handwriting (Beers et al., 2017), which should change with age towards an advantage for computer-keyboard typing. In line with Morken and Helland (2013), we did not expect differences in the number of self-corrections between dyslexic and control children.

Methods

Participants

Fifty-two children participated in the study, 22 children with DD (experimental group: 12 males, mean age=11.45 years, *SD*=1.22 years), and 30 typically developing children matched for chronological age (control group: 13 males, mean age 11.33 years, *SD*=1.02 years). The study includes only monolingual German-speaking children without any developmental disorder (except DD).

Children with DD were initially diagnosed with DD either by their local education authority, a psychologist, or an educational therapist. To this end, different cognitive and literacy measures were used, e.g., the Hamburg-Wechsler-Intelligenztest für Kinder – IV (HAWIK-IV, Petermann & Petermann, 2010), the Coloured Progressive Matrices (Raven, 1962), the Hamburger Schreibprobe (May, 2002), and the Lese- und Rechtschreibtest SLRT – II (Moll & Landerl, 2010). DD was moderate to severe according to the standards of the respective test procedures. In most children (*n*=17), impaired writing occurred combined with reading difficulties, while some children had isolated writing difficulties (i.e., dysgraphia, *n*=5).

Written informed consent was obtained from parents before the study besides children's verbal assent before actual testing. The local ethics committee approved the study (LEK 2014/19).

Procedure

Children were tested individually in a well-lit quiet room in two sessions for about 60 minutes each. They completed a writing-to-dictation task for real words and pseudowords and a copy-task in a computer-keyboard and a handwriting condition. As many German spelling assessments use gapped sentences in the dictation task (e.g., Deimel, 2002), this format was chosen. The copy task served as a control task to control writing speed (i.e., writing time) and always followed the dictation task. We counterbalanced the order of conditions (i.e., writing mode and lexicality) across participants.

In the typing (i.e., computer-keyboard) condition, a 15.6-inch Lenovo ThinkPad T530 laptop with a resolution of 1024x768 pixels was used at average viewing distance. Children solved the tasks by typing on a standard QWERTZ keyboard. We introduced task-relevant laptop functions (e.g., capitalization, deletion of incorrect entries) before the task. Accordingly, children had the same prerequisites for coping with the tasks. All computer-based tasks were programmed in C#, including key-logging. The resulting log file contained information about key-presses, presentation durations, and reaction times.

In the handwriting condition, children performed writing on a digitizing (Wacom Intuos 2) linked to a laptop and controlled by Eye and Pen 2 software (Alamargot, Chesnet, Dansac, & Ros, 2006; Chesnet & Alamargot, 2005, for a detailed description of the setup). This software-controlled experimental procedure tracked all writing movements and recorded various writing parameters (e.g., the pen's position on the tablet's surface, temporal information on each event conveyed by the tablet). Using a Wacom Ink Pen (inking pen), children wrote on a paper sheet on the tablet's surface.

In addition to the writing tasks, we assessed children's general cognitive ability and verbal working memory using HAWIK-IV's Processing Speed and Digit Span subtests (Petermann & Petermann, 2010). We also examined children's literacy skills by applying the Zürcher Lesetest-II (ZLT-II; Petermann et al., 2013). The latter included the reading of single words, pseudowords, and texts. The ZLT-II also allows for assessing RAN for both known (i.e., trained) and unknown visually presented stimuli (i.e., objects: a fork, a door, a spider). Verbal working memory was assessed by the syllable span (i.e., from two- to six-syllable pseudowords) for pseudowords (e.g., 'lofa', 'manupira' 'gekafesalita'). We administered all diagnostic tests according to the instructions described in the respective manuals.

Tasks

Writing to dictation. In the writing-to-dictation task, children completed gapped sentences (e.g., "The vampire put a ... in the girl's throat." [bite]). Sentences were presented visually and auditorily, followed by an auditory repetition of the target word. We instructed the children to read along with the sentence during dictation, wait until the target word's repetition, and then write or type in (depending on the condition) the respective target word. Overall, we administered 34 real words and 20 pseudowords, using two parallel test versions. Appendix A1 provides items and sentences for both test versions in German and English. Two practice items in each condition preceded all tasks. Table 1 provides information regarding the parallelization of the test sheets.

Table 1: Overview of parallelized test items

Copy task. The copy task always followed the writing-to-dictation task. We asked the children to copy the given text correctly with their average writing speed within a five-minute time limit. Children were allowed to revise within this time limit. Texts were counterbalanced across writing conditions and displayed on the laptop screen. Children wrote on lined paper with 2cm spacing between the lines to leave literally enough space for self-corrections in the handwriting condition and used the laptop's keyboard for typing. Texts were matched as accurately as possible (see Table 2 for the content description of the text in English). Appendix B provides the German texts from which the parallelization emerges. In total, German text corpora consisted of 43 words each (11 nouns, 7 verbs, and 5 adjectives) for both conditions, presented in five sentences.

Table 2. English translation of the parallelized texts for the Copy Task

General level analysis

Data processing. Data processing was performed separately for the computer- keyboard typing and handwriting conditions. We logged all keystrokes in the typing condition and recorded individual letters of each test word with their corresponding writing times. We documented self-corrections similarly (i.e., deleting letters and re-entering them). In the handwriting condition, each grapheme's writing duration in a test word was measured by determining when the writing process was started and finished.

In summary, the variables *spelling accuracy, writing times*, and the number of *self-corrections* entered into the data analysis. In terms of accuracy, we assessed spelling as either correct (scored 1) or incorrect (scored 0) concerning German spelling rules. Writing times were calculated by subtracting the times for corrections (i.e., the deletion of letters on the keyboard or the manual strike-through) from the overall word's writing time. We choose this procedure because times of self-corrections differ considerably between handwriting and typing per se. Subsequently, trimmed writing time for each test word was divided by the number of graphemes. This quotient (trimmed writing time/grapheme) entered the analysis as the dependent variable for writing time.

Descriptive group comparison. In addition to dyslexia diagnostics already obtained for the participating children, we examined between-group differences concerning general cognitive abilities, literacy skills, and RAN. In the first step, the Shapiro Wilk test (Shapiro & Wilk, 1965) indicated that distributions for cognitive ability, working memory, and literacy skills deviated significantly from the normal distribution. Accordingly, we used the Wilcoxon sign-rank test (Wilcoxon, 1945) for group comparisons. Bonferroni-Holm procedure (Holm, 1979) was applied to correct for multiple testing. Finally, we computed rank-biserial correlation as a measure of effect size for the Wilcoxon sign-rank test (equivalent to the Mann–Whitney U test, Wendt, 1968). The Type I error rate was set to alpha = .05.

Mode effect in typical and atypical writing. We investigated the mode effect in children with and without DD using (generalized) linear mixed models (G)LMM) on the overall *spelling accuracy*, *self-corrections*, and *writing times* using the R package *lme4* (Bates et al., 2014).

As fixed effects, we entered group (i.e., typically developing and dyslexic children) and mode (i.e., handwriting or computer-keyboard typing) at the subject level as well as lexicality (i.e., words and pseudowords) at the item level into the model. As random effects, we included random intercepts for both subjects and items.

The following covariates were considered control variables in the respective models: for both i) *spelling accuracy* and ii) *self-corrections* as dependent variables, we included children's sex and age as covariates on a subject level. For iii) *writing times* as a dependent variable, writing duration in the copy task was entered as a covariate in addition to sex and age. It is important to note that the copying time has been adapted to reading performance as lower reading performance will affect copy times. For this purpose, as assessed using the ZLT-II, text reading performance was added to the model as a covariate. This measure was employed to control the handling of handwriting and typing.

We applied the following model selection procedure: At first, we defined the baseline model, which controls for variability due to subjects and items (i.e., the model included only error terms for subjects and items). In R syntax, the baseline model appears as follows:

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Outcome ~ (1|subject) + (1|item)
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Then, we added fixed effects stepwise to this baseline model, depending on significance by excluding non-significant parameters. Likelihood-ratio tests allowed comparing the model fit. Subsequently, we included the covariates as additive terms in the model and finally compared this model with the full model considering all interactions of fixed effects and covariates. We repeated the same model selection procedure under the inclusion of the covariates. This procedure was identical for analyzing all interest variables (i.e., *spelling accuracy, writing times*, and *self-corrections*). Hence, the initial hypotheses were tested based on model comparisons.

Results:

Descriptive statistic

Children with and without DD were assessed on general non-verbal intelligence (i.e., assessed through processing speed), verbal working memory, and literacy skills (i.e., reading, syllabification, which refers to the task decomposing a word into its verbal syllables), and RAN. As expected, children with DD scored significantly lower in literacy tasks (i.e., reading and syllabification) and RAN (except for unknown material). Still, they did not differ significantly in processing speed (see Table 3). They also scored significantly below the control group in verbal working memory, most notably when assessed with lexical material. Table 3 presents group comparisons, statistical details, and effect sizes.

Table 3: Descriptive statistics per group on non-verbal intelligence and literacy skills.

Test sheet comparison

Before more detailed analyses, we conducted a two-way analysis of variance (ANOVA) to compare whether children's spelling performance (i.e., accuracy) differed between the mode of testing assessed using the two test sheets. Results indicated that the average number of correctly written words collected by hand and on the computer did not differ between test sheet A (handwriting: M=34.55, SD=9.58 and typing: M=32.77, SD=9.40) and test sheet B (handwriting: M=34.82, SD=10.60 and typing: M=35.97, SD=10.69), $F(2,101)<1$, ns. Accordingly, we considered both test sets as equally demanding. Furthermore, we used Bayesian methods to evaluate null effects, as described by Masson (2011). Bayesian analysis indicated a posterior probability of .88 for set and .86 for mode. Thus, there is evidence for the null hypothesis suggesting comparable test material.

Mode effect in typical and impaired writing

Table 4 gives an overview of mean group differences for writing mode and lexicality in *spelling accuracy, self-correction*, and *writing times*.

Table 4: Descriptive statistics per group on writing and spelling performance.

In the following, results of separate hierarchical (G)LMM are presented. Table 5 (Panel A-C) shows the overall terms considered in the models and their parameter values in the final models. Figure 1 (Panel A-C) shows the mean fixed effects coefficients from the final model for each group and the mean group differences from the original data. Appendix C describes the model selection procedure in detail.

Table 5: Analysis of spelling accuracy, self-corrections and writing times (A-C): parameter values for fixed effects and covariates added to the final model

For *spelling accuracy*, likelihood-ratio tests revealed the best fit for the model, including group, mode, and lexicality as fixed effects and sex and age as covariates. Table 5A provides estimates, standard errors, Z-statistics, and p-values of the final model. As shown in the table, group (β=-1.66) and mode (β=-0.16) significantly predicted lower *spelling accuracy*; children with DD wrote less accurately than their peers. Moreover, computer-keyboard typing resulted in more spelling errors compared to handwriting in all children. At the item level, the main effect for lexicality (β=0.89) indicated that writing words were significantly easier than writing pseudowords. We did not observe any significant interactions between model coefficients. Furthermore, sex (β=-0.73) and age (β=*0*.25) influenced spelling accuracy significantly. In both populations, male children performed less accurately than female children, and older children spelled more accurately than younger children.

For *self-corrections,* likelihood-ratio tests showed that the model, including group, mode, and lexicality as fixed effects predicted the data best. Table 5B provides model estimates, standard errors, Z-statistics, and p-values. Lexicality significantly influenced the number of *self-corrections*. Children self-corrected more frequently when writing words as compared to when writing pseudowords (β=0.33). Mode (β=2.80) and group (β=3.36) ended to affect self-corrections, with children with DD revising more often. Again, we did not observe any significant interactions between model coefficients. However, adding age and sex as covariates to the model did not improve the model fit.

For *writing times,* linear mixed models that included group, mode, and lexicality as fixed effects and age and copying time as covariates showed a good fit to the data. The base model was defined by including the copy times adapted for text reading performance. Consideration of sex in the model did not improve the fit. Nevertheless, the full model considering all interactions of these effects revealed a better fit. Crucially, for the variables age and reading performance, a four-way interaction was found with the group and copy time. This finding suggested that we might consider additional influences on *writing times*. However, interpretation of those interactions does not provide an unambiguous conclusion.

Table 5C provides model estimates, standard errors, *t*-statistic, and confidence intervals for the more parsimonious significant model according to the likelihood ratio tests. Model coefficients showed that typing mode significantly predicted longer *writing times* (β=2066.63), meaning that typing on the computer keyboard was, on average, about 2 seconds slower per letter than typing by hand. Writing and typing times did not differ significantly between groups, but children who worked more slowly on the copy task also showed longer writing times in writing-to-dictation (β=0.68). Additionally, a significant interaction occurred between age and mode (β=-162.79). This interaction indicated that, for older children, the mode effect (i.e., increased writing times when typing on the computer keyboard) was smaller than for younger children.

Fig 1: Group means from original data without consideration of covariates for *spelling accuracy* (A), *writing times* (B), and *self-corrections* (C) depicted as grey dots.

Discussion of holistic effects

In the following, we will discuss the result of the holistic approach. Our results substantiated that writing mode affects both spelling accuracy and writing times equally in all children.

In terms of *spelling accuracy*, computer-keyboard typing was more error-prone than handwriting, significantly reducing *spelling accuracy* (see Feng et al., 2019; Freeman et al., 2005; Goldberg et al., 2003). Thereby, our results differed from previous findings by Frahm (2013), who did not find an influence of writing mode for 5th-grade children. The following reasons may hold for the inconsistent findings: In contrast to Frahm (2013), we chose a within-subject design. Within-subject designs usually have a higher test power and can detect even smaller effects (Lottridge et al., 2008). The study design by Frahm (2013) probably does not allow capturing an existing mode effect. Furthermore, qualitative error analysis revealed that some test words seem to be more responsive to mode effects than others (Kröhne & Martens, 2011). Possibly, item selection in the two studies may differ in this respect.

In terms of *writing times*, computer-keyboard typing significantly increased latencies consistently for both groups of children. This increment was less pronounced in older children, probably due to more computer experience (cf. Connelly et al., 2007; Goldberg et al., 2003; Horne et al., 2011; Mogey & Hartley, 2013). Horne and colleagues (2011) found that children older than 14 years significantly benefit from computer experience in computer-keyboard typing. The children in the present study were younger than 14 years, which may explain increased typing times. In this vein, observation of standard errors, which also decreased with age in the computer-keyboard condition, may support this explanation. Variations in standard errors can also express individual differences and different experiences with typing instruction in school. Typing instructions also may reinforce the mode effect on writing times (Connelly et al., 2007; Marom & Weintraub, 2015; Weigelt-Marom & Weintraub, 2018). Although this finding is not as crucial for writing at the single word level as for other linguistic levels (e.g., text level), typing instruction should be considered in subsequent studies.

In terms of the *number of self-corrections*, a trend indicated that typically and atypically developing children tended to self-correct more often during computer-keyboard typing. Following the current literature (Goldberg et al., 2003; Morken & Helland, 2013), this trend suggested that although children with DD revised in the same manner as typically developing children, the final product was of lower spelling quality.

Apart from that, the following results were obtained consistently for both writing modes: In both groups, spelling errors significantly decreased with age. Older children spelled more accurately than younger children, which is well in line with previous findings (Feng et al., 2019; Horne et al., 2011; Russell, 1999). However, children with DD committed significantly more spelling errors reflecting DD symptoms (e.g., Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008b; Lyon et al., 2003). Furthermore, male children performed less accurately (e.g., Berninger & Fuller, 1992; Berninger et al., 2008a for similar findings). Additionally, all children struggled with pseudoword writing compared to real words (i.e., sub-lexical processing was more difficult than lexical processing). Pseudowords do not access semantics (Binder et al., 2009) or lexical knowledge. Moreover, writing pseudowords requires phonological encoding, which poses higher cognitive demands (Newman & Twieg, 2001). Hence, sub-lexical processing was more error-prone than lexical processing (cf. Landerl, 1997).

Taken together, the results of the holistic analysis provided converging evidence that the writing of typically developing children and children with DD is equally affected by the mode of writing. This effect significantly impacted *spelling accuracy* and *writing times*, but not on the number of *self-corrections*, depending on the children's age. Crucially, qualitative error analyses revealed differences between test words and spelling rules regarding error rates and the writing mode's potential influence. The latter observation prompted the second step in this study.

Second step: Consideration at the rule-specific level

Objectives

The different spelling rules considered in this study put specific demands on processes associated with correct spelling. For instance, writing capital letters in nouns and nominalizations, assessed by the spelling rule capitalization, requires an additional motoric movement to press the Shift-key on the computer keyboard. The realization of the spelling rules consonant doubling or lengthening signs demands knowledge about the phoneme-grapheme assignment. In the German orthography, writing of a double consonant indicates that the vowel's pronunciation, preceding the double consonant, is short. Writing of a lengthening sign, in contrast, suggests that the pronunciation of the vowel, which precedes the lengthening sign, is long (e.g., Stiel [ʃti:l] – still [ʃtɪl]. Morphological knowledge about the devoicing of a final voiced consonant at the end of a syllable or a word is assessed by the spelling rule final obstruent devoicing. Finally, knowledge of exceptions to the regular grapheme-phoneme assignment in German is evaluated based on rule words. Correct spelling requires mastering all of these orthography-related processes.

In our second step of analyses, we aimed at evaluating whether writing mode modulates those cognitive processes differentially. To this end, we assessed the mode effect on children's writing performance separately for the following spelling rules: capitalization (N=34 test words), consonant doubling (n=16), lengthening (n=7), rule words (n=8 words), and final obstruent devoicing (n=6).

Methods

Data Processing

At a rule-specific level, we assessed whether the relevant spelling rule was correct or incorrect for each test word. For instance, '**voll**' [Engl. full] was assessed concerning (inner sentence) capitalization and consonant doubling, while the other spelling rules did not apply to this particular test word. For instance, for consonant doubling, it was assessed whether the double consonant was realized correctly irrespective of whether the overall spelling was correct (i.e., whenever the test word '**voll**' [Engl. full] was written like '**foll**', double consonant spelling was assessed as correct and scored 1, although the overall spelling was not correct, but a spelling such as **'vol'** was considered incorrect and scored 0).

We performed similar (general) linear mixed model analyses as in the holistic approach examining again, *spelling accuracy, writing times*, and *self-corrections* for each specific German spelling rule. We conserved test words only relevant when the respective rule was applicable [e.g., capitalization applied to all test words (N=34), whereas consonant doubling appeared in n=16 test words]. We applied the same stepwise data modeling procedure: We first defined the baseline model for each spelling rule and then included the fixed effects on the subject and item level. Subsequently, we added the covariates to the model as additive terms. We then compared the final model with the full model considering all interactions of fixed effects and covariates. Appendix D 1-5 shows the model selection procedure for each spelling rule in detail.

Results

Concerning *spelling accuracy*, the most striking result was that writing mode predicted significantly lower spelling accuracy for capitalization (β=-0.61) only. However, spelling accuracy assessed by other spelling rules (i.e., lengthening, consonant doubling) did not differ between both writing modes. Two other findings for capitalization supported this result. First, a significant main effect for word-class [nouns vs. other words (β=3.81)] indicated that noun word writing was significantly more difficult in both conditions. This effect was even more pronounced for pseudowords, as suggested by the significant interaction of lexicality and word class (β=-1.38). Second, the significant interaction of mode with word-class (β=1.40) indicated that noun word typing was even more difficult. Only for capitalization, the full model yielded a better fit.

Furthermore, the variable group significantly predicted lower spelling accuracy for all spelling rules [capitalization (CAP): β=-0.99, consonant doubling (GEM): β=-1.89, lengthening

(LEN): β=-1.90 and rule words (RULE): β=-1.26 except for devoicing (DEV): β=-0.61]. Children with DD wrote less accurately than the control children. Furthermore, sex (CAP: β=-0.59, GEM: β=-1.02, LEN: β=-0.86 and RULE β=-0.72) and age (CAP: β=0.19, GEM: β=0.39, LEN: β=0.36, and RULE β=0.28) influenced spelling accuracy: in both groups, male performed less accurately, and older children spelled more accurately than younger children.

At the item level, writing words was significantly easier than writing pseudowords as indicated by the significant main effect for lexicality in all spelling rules (CAP: β=1.82, GEM: β=2.78, LEN: β=3.28), again except for devoicing (β=0.74). Table 6A provides model estimates, standard errors, Z-statistics, and *p*-values for each spelling rule.

For *self-corrections*, we observed a significant main effect of writing mode (i.e., self-corrections increased during computer-keyboard typing) for all spelling rules (CAP: β=0.98, GEM: β=0.82, LEN: β=2.80 and RULE: β=1.01) except for devoicing (β=1.86). Two particularities occurred for capitalization: Lexicality significantly influenced the number of *self-corrections* (i.e., more self-corrections for real words than pseudowords, β=0.49). Second, the number of self-corrections was lower for non-nouns (β=-1.50). For rule words, sex (β=9.23) significantly influenced the number of self-corrections. In particular, male children self-corrected more often than female children. Table 6B gives model estimates, standard errors, *t*-statistics, and confidence intervals for the specific spelling rules.

For *writing times*, we observed consistent results for all spelling rules. Writing mode predicted longer writing times (CAP: β=1936.94, GEM: β=2016.33, LEN: β=1562.86, DEV: β=1438.95, and RULE: β=1525.50) for both groups. Computer-keyboard typing was, on average, about 1500 – 2000ms per letter slower than writing by hand. Children who worked more slowly on the copy task also showed generally longer writing times in writing-to-dictation (CAP: β=1.33, GEM: β=1.32, LEN: β=1.58, DEV: β=1.20, and RULE: β=1.25).

Moreover, older children tended to write faster than younger children (CAP: β=-66.17, GEM: β=-51.96, LEN: β=-45.13, DEV: β=-46.02, and RULE: β=-57.80). Additionally, we found a significant interaction between age and mode for capitalization (β=-137.13). This interaction indicated that the mode effect (i.e., increased writing times during computer-keyboard typing) was about 130ms second smaller for older children than for younger children. Finally, mode and lexicality significantly interacted. Crucially, these interactions differed in direction between capitalization (β=99.16) and the other spelling rules (GEM: β=-149.48, LEN: β=-104.22, DEV: β=-99.55, and RULE: β=-89.83), indicating that the mode effect was longer for capitalization for real words but shorter for the rest.

Regarding likelihood ratio tests, the full model considering all model terms' interactions yielded a better fit for capitalization only. For all other spelling rules, model terms included in our simpler model might be sufficient to explain empirical data. Table 6C provides model estimates, standard errors, *t*-statistics, and confidence intervals for the specific spelling rules.

Discussion of rule-specific effects:

The rule-specific approach allowed a more fine-grained evaluation of specific writing mode influences on complementary linguistic processes (e.g., phonological awareness, morphological principles, and rule knowledge as assessed by different spelling rules).

In terms of spelling accuracy, the most striking result was that the mode effect, observed in the holistic analysis, was evident for capitalization only, but not for any other spelling rules. The following reasons may explain this result: First, capitalization of letters is one of the most significant German-language difficulties and the most common source of spelling errors (e.g., Guenther & Nuenke, 2005). Second, typing capital letters differs significantly from all other spelling rules in written language (i.e., by pressing the additional 'Shift' key on the computer keyboard). Third, simplifying written language by avoiding capitalizing initial letters when using digital social media (Wood et al., 2014) might also have contributed to this result. As the literature provides no consistent view of how much such textism affects spelling accuracy in more formal contexts, we cannot neglect this potential influence.

However, this additional keypress seemed to affect children's spelling performance and might reflect a (negative) mode effect. This insight is significant, in particular, when comparing the results of analog and digital writing assessments. In contrast, consonant doubling and lengthening, primarily based on phonological awareness (Moll et al., 2009), were not affected by writing mode. The same was evident for morphological principles as assessed with the final obstruent devoicing (i.e., requiring a derivation of the word) and rule words, respectively. All other results regarding spelling accuracy were identical to those of the first step of analyses.

In terms of *writing times*, the rule-specific results corroborated findings from the first step analysis for the mode effect (Goldberg et al., 2003; Wollscheid et al., 2016). Writing times were significantly affected by writing mode and specifically increased for typing in all spelling rules equally for both children groups. Moreover, the increase in writing times depended on the children's age and computer experience.

Contrary to the first step of analyses, the number of self-corrections was influenced significantly by writing mode for all spelling rules, except for final obstruent devoicing. Computer-keyboard typing increased self-correction behavior consistently in both groups of children. The influence of sex and age on the number of self-corrections was apparent only for rule words indicating that boys revised rule words more often than girls. However, this difference declined with age. Sex differences in language skills were reported repeatedly. Neuroimaging results suggested that boys and girls rely on different brain areas for accurate language task performance (Burman et al., 2008). Boys seemed to rely on a modality-specific (i.e., visual or auditory) network, whereas girls used supra-modal language networks, representing a more abstract, conceptual knowledge of words. Writing rule words requires a direct writing strategy (i.e., word retrieval from a long-term orthographic lexicon, Ellis, 1982). In case the lexical entry for the target word has not yet been established (Guenther & Ludwig, 1994), children may use alternative sub-lexical writing strategies. These strategies, however, are not successful in most cases. Unlike girls, boys might rely more on such sub-lexical writing strategies when they are not entirely sure about the correct spelling. Subsequently, they self-correct more to match the word to the lexical entry. Additionally, older children revised less-frequently on rule words, probably because the number of lexical entries increases with age (e.g., Nippold, 2002).

General Discussion

In the present study, we evaluated handwriting and typing skills in typically developing children and children with DD from a more general level and rule-specific level, directly comparing the mode effect (i.e., the difference between handwriting and computer-keyboard typing).

At first glance, writing mode influenced overall writing time (i.e., speed) and the number of self-corrections. Children in both groups wrote more slowly on the computer keyboard than by hand, which corresponds to previous research (i.e., Alves et al., 2016; Connelly et al., 2007; Feng et al., 2019; Wollscheid et al., 2016). We also replicated the modulating influence of age on the writing mode (Goldberg et al., 2003; Horne et al., 2011). Concerning spelling accuracy, typing increased spelling errors for typically developing children (but see Frahm, 2013) and children with DD (e.g., Berninger et al., 2009) to the same extent. There was no difference between the groups regarding the mode effect. However, children with DD underperformed in writing as compared to their peers in both writing modes.

At a second glance, somehow, contradictory findings were observed. The rule-specific analysis indicated that writing mode only affected spelling accuracy through capitalization.

Typing capital letters on the computer keyboard differs motorically from typing necessary for all other spelling rules. The motor component requires a certain degree of automatization, which children of both groups seemed to master comparably well. Crucially, this motor aspect does not affect the complementary linguistic aspects of writing, such as phonological awareness, morphological principles, and rule knowledge. Therefore, writing mode may not have affected performance on spelling rules other than capitalization. However, this can only be determined by evaluating each spelling rule individually, which avoids generalization from one spelling rule to another. Besides, capitalization occurs in every single test word in a standard writing assessment on the sentence level. Consequently, capitalization may superimpose other spelling rules in a holistic analysis. For this reason, the holistic analyses in our first step of analyses were not able to detect this differential mode effect.

Taken together, the present results suggest different graphomotor demands posed by various writing media (e.g., assigning the fingers to designate keys while typing), which needs to be considered in the assessment of writing and spelling performance. This is in line with recent observations by Rodriguez et al. (2019), who found that the writing mode (i.e., pen and paper, pen and tablet, and finger and tablet in their study) influences processing times but not accuracy in clinical testing in adults. These graphomotor requirements, however, seem to affect typically developing children and children with DD comparably. As such, computerized and paper-pencil tests seem equally suitable to assess writing skills in children. This conclusion is of particular importance for the application of digital media in educational and therapeutic contexts.

Finally, it is worth mentioning that digital learning applications fostering writing and spelling skills promise to engage children with orthography tasks and facilitate learning (e.g., Jung et al., 2016). According to our findings, learning progress can be assessed either traditionally using paper-pencil tests or digitally using computerized tests, whereby results should be comparable when applying a rule-specific analysis. However, for the use of spell-checkers, our results indicate that without these additional, mainly visual support, children with DD may not benefit from computer-keyboard typing. Computer-keyboard typing does not facilitate writing by itself, and spell checkers do not prevent children from making mistakes. However, the combined use of both can visualize spelling errors, and thus, cue self-corrections, which argue for their application in educational and therapeutic settings as a compensatory instrument.

When interpreting present results, it is worth considering some limitations. First, in the present study, writing-to-dictation was assessed on the word level. As such, we did not evaluate text generation or planning processes. Therefore, we are cautious about generalizing from our results to the level of text generation, even though they are in line with the recent literature (e.g., Connelly et al., 2007; Wollscheid et al., 2016; but see Sumner et al., 2013). As such, it would be desirable to pursue further the intra-individual effect of the writing mode on these higher lexical levels. Second, we made conclusions based on the age of the children about their possible computer experience. The use of a standardized questionnaire (e.g., INCOBI-R, Richter, Naumann, & Horz, 2010) would have been more advantageous. However, conclusions on computer experience seem warranted as keyboard writing times decreased with children’s age. Third, there are differences in how children learn to handwrite, e.g., cursive writing (e.g., 'German Schreibschrift') and block letter writing (e.g., 'German Druckschrift'). The written grapheme in the block letter writing is visually similar to typed graphemes, while for italic handwriting, some letters differ from the typed (i.e., generic) form. In our study, we did not explicitly distinguish between these writing types. Accordingly, we cannot draw any conclusions in this respect. A final assumption might suggest that the mode effect varies in different languages. In German, where capital letters are widespread compared to other languages, this influence may be more pronounced than in other languages. Future cross-linguistic studies have the potential to address this issue.

Conclusion and Future Prospects

Digital technology has changed writing habits to such an extent that the question arises whether it needs to be considered when assessing writing and spelling skills. In this study, we investigated the influence of writing mode (i.e., handwriting vs. computer-keyboard typing) on spelling performance in typically developing children and children with DD at a general and a rule-specific level.

At both levels of analysis, we found that children of the same age group (i.e., secondary school children) wrote comparably fast irrespective of whether they had writing problems. Additionally, both groups showed slower *writing times* on the computer. The mode effect in *self-correction* behavior was more pronounced when assessed at the rule-specific level. Again, children with DD did not differ from controls.

The sole difference between children with and without DD was their *spelling accuracy,* which was more pronounced from a rule-specific analysis. Against this background, we suggest focusing on individual spelling rules (and thus on complementary linguistic processes) in the assessment of writing across modes.

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Table 1: Overview of parallelized test items

Sheet	N	Lex.	Example	Word category			Number of syllables				Spelling rules				
				NOUN	VERB	ADJ.	1	2	3	> 3	CAP	COD	LEN	DEV	RULE
Set A	34	Word	voll	16	9	9	9	15	8	3	34	16	7	5	8
	22	Pseudo	boff	10	8	4	7	9	4	0	20	4	4	2	0
Set B	34	Word	hell	16	9	9	7	15	8	3	34	16	7	6	8
	22	Pseudo	humm	10	8	4	7	9	4	0	20	4	2	2	0

Note: Test sheets were parallelized according to Lex=Lexicality (word or pseudoword), word category (noun, verb, ADJ.=adjectives), number of syllables, and spelling rules (CAP=Capitalization, COD= Consonant doubling, LEN=Lengthening, DEV=Final obstruent devoicing, RULE= Rule words.

Table 2. English translation of the parallelized texts for the *Copy Task*

Text A:	**Text B:**
Bello and the locomotive	Wuffi and the lawnmower
The mother asks her son Felix to go for a walk with Bello now.	The mother asks her son Lukas to mow the lawn today.
But Felix has no desire at all. He prefers to play with his new locomotive. What does Bello do? The poor dog sits impatiently with his leash in front of the door and waits.	But Lukas has no desire at all. He prefers to play with his new football. His faithful dog Wuffi comes into the garden. He sits down and waves his tail joyfully.

Table 3: Descriptive statistics per group on non-verbal intelligence and language skills.

	Dyslexia		Controls			
	Mean	**SD**	**Mean**	**SD**	**W**	**r**
Verbal working memory						
Digit span forward	5.05	1.36	6.16	1.05	505.50**	.53
Digit span backward	3.59	2.64	4.40	2.21	479.50*	.45
Syllable span (pseudowords)	3.36	0.65	4.92	0.80	605.00**	.83
General cognitive ability						
Processing speed (PR)	64.03	15.17	68.84	16.53	395.50	.19
Reading						
Word reading time	56.10	33.90	82.00	22.79	426.50*	.48
Word reading accuracy	20.20	22.32	81.33	14.58	643.00**	.94
Pseudoword reading time	48.45	33.01	81.73	21.90	527.50*	.59
Pseudoword reading accuracy	12.70	10.48	79.91	17.18	653.50**	.98
Text reading time	67.05	31.72	97.26	4.33	619.50**	.87
Text reading accuracy	10.25	10.77	68.83	20.09	653.00**	.97
Hyphenation						
Verbal (PR)	48.48	33.02	73.26	24.49	470.00*	.42
Written (PR)	29.63	23.39	77.16	18.91	607.50**	.84
Rapid automatized naming (RAN)						
Known material (PR)	67.50	27.35	88.43	11.76	477.50*	.44
Unknown material (PR)	90.86	22.44	95.86	11.40	377.50	.14
Letters (sec)	20.59	4.21	16.93	4.01	159.50**	.52
Numbers (sec)	33.27	4.60	27.70	5.46	149.50*	.54

Note: Table 3 provides the mean percentage ranges (PR) of the standardized (sub-)tests for processing speed and language skills. Accuracy measures in the Zürcher Lesetest II are given in percentile bands. To compare the performances of both groups, the mean of the respective percentile bands was calculated. Contrasts (e.g., verbal working memory, reading, etc.) were corrected for multiple testing using the Bonferroni Holm procedure. * $p<.05$ and ** $p<.001$.

Table 4: Descriptive statistics per group on writing and spelling performance.

	Mode	Lexicality	Accuracy (in %)	Writing Times (ms/grapheme)	Self-Corrections (quantity)
Dyslexia	Writing	Word	54.81 (49.80)	565.14 (249.49)	11.22 (31.59)
		Pseudo	41.59 (49.34)	537.65 (234.47)	8.63 (28.12)
	Typing	Word	54.67 (49.81)	958.06 (781.84)	20.58 (40.46)
		Pseudo	39.31 (48.90)	959.22 (722.73)	15.45 (36.18)
Controls	Writing	Word	81.64 (38.72)	554.64 (223.78)	3.72 (18.94)
		Pseudo	69.16 (46.21)	519.14 (223.54)	4.16 (19.99)
	Typing	Word	79.31 (40.52)	792.75 (635.02)	18.13 (38.55)
		Pseudo	64.51 (47.89)	855.45 (521.97)	12.66 (33.28)

Note: Table 4 provides group means and standard deviations in parentheses for spelling accuracy (in %), writing times per grapheme (in ms), and mean the absolute number of self-corrections.

Table 5: Analysis of spelling accuracy, self-corrections and writing times (A-C): parameter values for fixed effects and covariates added to the final model

A)	**Spelling accuracy**	**Estimate**	**SE**	***Z***	***P***	
	Intercept	-1.37	1.15	-1.19	0.23	
	Sex (male)	-0.73	0.22	-3.30	<.001	
	Age	0.25	0.10	2.51	0.01	
	Group (dyslexia)	-1.66	0.22	-7.51	<.001	
	Lexicality (words)	0.89	0.27	3.26	<.001	
	Mode (typing)	-0.16	0.07	-2.20	0.03	
B)	**Self-Corrections**					
	(Intercept)	-6.20	1.73	-3.59	0.00	
	Mode (typing)	2.80	1.68	1.66	0.10	
	Group (dyslexia)	3.63	2.13	1.70	0.09	
	Lexicality (words)	0.33	0.10	3.21	0.00	
C)	**Writing times**	**Estimate**	**SE**	***t-value***	**Confidence interval**	
					Lower	Upper
	(Intercept)	702.10	488.58	1.44	-227.73	1631.60
	Copy time	0.68	0.18	3.86	0.34	1.04
	Text reading	-1.35	1.46	-0.92	-4.12	1.42
	Age	-13.36	41.06	-0.33	-91.55	64.75
	Mode (typing)	2066.63	277.86	7.44	1520.15	2608.68
	Age * Mode	-162.79	24.45	-6.66	-210.47	-114.70

Note: Only significant parameters resp. Interactions from the preferred model are presented in the table.

Table 6: Rule specific analysis of spelling accuracy, self-corrections, and writing times (A-C): significant parameter values for fixed effects and covariates added to the final models.

	Capitalization				Consonant doubling				Lengthening				Devocing				Rule words			
A) Spelling accuracy	**Est.**	**SE**	***Z***	***p***	**Est.**	**SE**	***Z***	***p***	**Est.**	**SE**	***Z***	***p***	**Est.**	**SE**	***Z***	***p***	**Est.**	**SE**	***Z***	***p***
Intercept	-1.16	1.49	-0.78	0.44	-2.93	1.54	-1.90	0.06	-2.60	1.35	-1.92	0.05	3.54	0.67	5.32	0.00	-1.40	1.73	-0.81	0.42
Sex (male)	-0.59	0.29	-2.06	0.04	-1.02	0.29	-3.55	0.00	-0.86	0.26	-3.31	0.00	-	-	-	-	-0.72	0.33	-2.19	0.03
Age	0.19	0.13	1.48	0.14	0.39	0.13	2.98	0.00	0.36	0.12	3.12	0.00	-	-	-	-	0.28	0.15	1.88	0.06
Mode (typing)	-0.61	0.16	-3.69	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Group (dyslexic)	-0.99	0.28	-3.49	0.00	-1.89	0.29	-6.57	0.00	-1.60	0.32	-5.04	0.00	-0.61	0.62	-0.97	0.33	-1.26	0.33	-3.79	0.00
Lexicality (words)	1.82	0.40	4.61	0.00	2.78	0.53	5.25	0.00	3.28	0.58	5.70	0.00	0.74	0.74	0.99	0.32	-	-	-	-
Word class (non nouns)	3.81	0.47	8.08	0.00	-	-	-	-	-	-	-	-					-	-	-	-
Lexicality * Group	-	-	-	-	-	-	-	-	-1.44	0.46	-3.13	0.00	-1.37	0.67	-2.05	0.04	-	-	-	-
Lexicality * Mode	0.49	0.23	2.16	0.03	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lexicality * WordClass	-1.38	0.61	-2.27	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WordClass * Mode	1.40	0.41	3.40	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

B) Self-corrections	**Est.**	**SE**	***Z***	***p***	**Est.**	**SE**	***Z***	***p***	**Est.**	**SE**	***Z***	***p***	**Est.**	**SE**	***Z***	***p***	**Est.**	**SE**	***Z***	***p***
(Interc.)	-4.50	0.28	-16.37	0.00	-4.83	0.38	-12.83	0.00	-6.63	1.04	-6.38	0.00	-14.73	5.47	-2.69	0.01	-6.31	2.57	-2.45	0.01
Sex (male)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9.23	4.00	2.31	0.02
Age	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.21	0.22	0.95	0.34
Sex * Age	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.82	0.35	-2.32	0.02
Mode	0.98	0.20	4.80	0.00	0.82	0.38	2.17	0.03	2.80	1.00	2.80	0.01	1.86	1.63	1.14	0.25	1.01	0.35	2.91	0.00
Lexicality (words)	0.49	0.21	2.34	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Word class (non nouns)	-1.50	0.22	-6.73	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

C) Writing time	**Est.**	**SE**	***t***	***ConfInt***		**Est.**	**SE**	***t***	***ConfInt***		**Est.**	**SE**	***t***	***ConfInt***		**Est.**	**SE**	***t***	***ConfInt***		**Est.**	**SE**	***t***	***ConfInt***	
(Intercept)	1248.84	410.28	3.04	452.37	2045.91	1007.48	413.52	2.44	210.96	1803.64	949.32	374.19	2.54	222.72	1676.97	922.02	315.05	2.93	312.18	1532.90	1064.90	580.92	1.83	-60.11	2191.37
Copy time	1.33	0.23	5.69	0.87	1.79	1.32	0.23	5.64	0.87	1.78	1.58	0.42	3.75	0.76	2.44	1.20	0.33	3.69	0.56	1.86	1.25	0.60	2.09	0.08	2.46
Text reading	-1.69	1.31	-1.29	-4.23	0.86	-1.32	1.32	-1.00	-3.86	1.22	-1.49	1.08	-1.38	-3.61	0.61	-1.48	0.99	-1.50	-3.40	0.44	-1.71	1.81	-0.95	-5.22	1.80
Age	-66.17	32.77	-2.02	-129.81	-2.51	-51.96	33.63	-1.55	-116.73	12.80	-45.13	29.52	-1.53	-102.51	12.25	-46.02	25.23	-1.82	-94.86	2.87	-57.80	46.55	-1.24	-147.93	32.42
Mode (typing)	1936.94	243.27	7.96	1459.44	2412.75	2016.33	269.79	7.47	1486.39	2543.68	1562.86	353.38	4.42	867.05	2252.18	1438.95	262.49	5.48	921.91	1951.90	1525.50	483.99	3.15	571.88	2470.02
Age * Mode	-137.10	21.17	-6.48	-178.50	-95.54																				
Lexicality * Mode	99.16	33.24	2.98	33.95	164.19	-149.84	23.57	-6.36	-195.90	-103.54	-104.22	30.87	-3.38	-164.43	-43.44	-99.55	22.95	-4.34	-144.36	-54.34	-98.93	42.30	-2.34	-181.44	-15.57

Note: Only significant parameters resp. interactions from the preferred model are presented in the table.

APPENDIX A:

Appendix A1 gives an overview of the parallelized test words and sentences used in the two test sets for handwriting and typing.

Table A1: Real words: item set A.

N	Cat.	Test word	CAP	COD	LEN	DEV	RULE	Sentence	English translation
P1	N	Zeh	x		x			Petra trat mir auf meinen großen ...	Petra stepped on my big … (toe)
P2	V	rollt	x	x				Die Billardkugel … ins Loch.	The billiard ball … into the hole. (rolls)
1	N	Pralinen	x				x	Oma liebt Süßes, am meisten mag sie ...	Grandma loves sweets. She likes ... the most. (pralines)
2	N	Entlassung	x	x				Es ist traurig, wenn einem Arbeiter mit der … gedroht wird.	It is sad when a worker is faced with a … (dismissal)
3	N	Zuckerwatte	x	x				Auf dem Jahrmarkt essen viele Leute süße ...	At the fair, many people eat sweet …(candyfloss)
4	N	Fernrohr	x		x			Die Sterne kann man am besten durch ein … sehen.	Stars are best seen through a … (telescope)
5	N	Schimmelkäse	x	x				Ein Milchprodukt, das streng riecht, ist ...	A dairy product that smells strong is … (mouldly cheese)
6	N	Dieb	x			x		Die Handtasche wurde von einem … geklaut.	The purse was stolen by a … (thief)
7	N	Geburtstag	x			x		Meist gibt es einen Kuchen zum ...	Usually, there is a cake for your … (birthday)
8	N	Abfall	x	x		x		Eine Bananenschale ist ...	A banana peel is … (garbage)
9	N	Nachsitzen	x	x				Wenn man zu viel Quatsch macht, drohen manche Lehrer mit ...	Some teachers threaten ... if you do too much silliness. (detention)
10	N	Rechnen	x					Mit Bruchzahlen ist das … schwieriger als mit ganzen Zahlen**.**	Fractions are more difficult to … than integers. (calculate)
11	N	Baby	x				x	In der Wiege schläft ein ...	In the cradle sleeps a … (baby)
12	N	Chips	x				x	Ich könnte pfundweise … essen.	I could eat a pound of …(chips)
13	N	Portion	x				x	Im Sommer isst man gerne eine große … Eis.	In summer you like to eat a large … of ice cream. (portion)
14	N	Garage	x				x	Zum Schutz steht das Auto in der ...	The car is in the … for protection. (garage)
15	N	Mus	x				x	Die reifen Äpfel kochen wir zu ...	We cook the ripe apples to … (applesauce)
16	N	Lok	x				x	Die Waggons werden von der … gezogen	The wagons are pulled by the … (locomotive)
17	V	klappern	x	x				Hör auf mit den Töpfen zu …!	Stop … with the pots! (clattering)
18	V	schleppt	x	x				Fin keucht, weil er die Kisten ...	Fin gasps because he's …. crates. (dragging)
19	V	beißen	x					Hunde, die bellen, … nicht.	Dogs that bark don't … (bite)
20	V	dehnen	x		x			Vor dem Sport sollte man die Muskeln ….	Before doing sports, you should ... your muscles. (stretch)
21	V	schaffen	x	x				Wenn alle mitmachen können wir es zusammen ...	If all of us cooperate, we can … it together (do).
22	V	verspritzen	x	x				Beim Patronenwechsel bin ich vorsichtig, ich will die Tinte nicht ...	I'm careful when changing cartridges; I don't want to … the ink. (splash)
23	V	malt	x					Oma freut sich, wenn Lisa ein Bild für sie ...	Grandma is happy when Lisa … a picture for her. (draws).
24	V	bieten	x		x			Will man eine Auktion gewinnen, muss man hoch ...	If you want to win an auction, you have to … high. (bid)
25	V	erzählst	x		x			Die Geschichten sind immer spannend, wenn du sie ….	The stories are always exciting when you … them. (tell)
26	A	grässlich	x	x				Das verbrannte Essen schmeckte ...	The burnt food tasted … (awful)
27	A	gierig	x		x	x		Hungrige Tiere sind … auf Essen.	Hungry animals are … for food. (greedy)
28	A	verwirrend	x	x		x		Das Durcheinander ist	The mess is … (confusing).
29	A	näher	x		x			Von Italien nach Frankreich ist es … als vom Mond zur Erde.	From Italy to France it is ... then from the moon to the earth. (closer)
30	A	entsetzliche	x	x				In den Nachrichten kam die … Meldung von einem Erdbeben.	The news reported the …news of an earthquake. (terrible)
31	A	stiller	x	x				Es ist viel zu laut hier, könnt ihr nicht … sein?	It's way too loud in here, can't you be …? (quiet)
32	A	schick	x	x				Für die Hochzeit macht sich die Braut ...	For the wedding, the bride ...(dresses up)
33	A	voll	x	x				Schenke mir mein Glas bitte ganz ...	Give me a … glass, please. (full)
34	A	cool	x				x	Seinen neuen Haarschnitt findet Hannes richtig ...	Hannes thinks his new haircut is really … (cool)

Note: The test words were preceded by two practice trials (P). The Category (CAT.) column specifies if the test word was used as a noun, verb, or adjective in the sentence.

Table A2: Real words: item set B.

N	Cat.	Test word	CAP	COD	LEN	DEV	RULF.	Sentence	English translation
P1	N	Biss	x	x				Der Vampir versetzte dem Mädchen einen ... in den Hals.	The vampire put a ... in the girl's throat. (bite)
P2	V	fiel	x		x			Lilo weinte heftig als sie vom Pferd ...	Lilo cried violently as she was ... from the horse. (fall)
1	N	Mandarinen	X				x	Zu Weihnachten gibt es viele Nüsse und ...	At Christmas, there are many nuts and ... (mandarins)
2	N	Überschwemmung	x	x				Wenn ein Fluss über die Ufer tritt, gibt es eine ...	When a river overflow, there is a ...(flood)
3	N	Trockenfutter	x	x				Ein Hase bekommt Salat und ...	A hare gets lettuce and ... (dry food)
4	N	Eselsohr	x		x			Eine umgeknickte Seite eines Buches nennt man ...	A folded page of a book is called ... (dog`s ear)
5	N	Nummernschild	x	x		x		Jedes Auto muss ein ...haben.	Every car must have a ... (number plate)
6	N	Seitenhieb	x		x	x		Weil ich ihn ärgerte, versetzte mir mein Sitznachbar einen...	Because I annoyed him, my seat neighbor gave me a … (side blow)
7	N	Zwerg	x			x		Im Märchen taucht oft ein kleiner … auf.	A small ... often appears in fairy tales. (dwarf)
8	N	Nähe	x		x			Timo wollte nicht alleine sein, darum war immer jemand in seiner ...	Timo never wants to be alone, so someone was always … (around).
9	N	Üben	x					Ohne ...wird keiner ein Meister.	Without … no one becomes a master. (practice)
10	N	Beschmutzen	x	x				Im Park ist das ... der Bänke verboten.	It is forbidden to … the benches in the park. (dirty)
11	N	Pony	x				x	Auf der Weide steht ein kleines ...	On the pasture stands a small ... (pony)
12	N	Chili	x				x	Nimm für das Essen bitte wenig ...	Please take a little … for the food (chili)
13	N	Mumie	x				x	Die Besucher im Museum betrachten eine schaurige ...	The visitors in the museum look at a gruesome … (mummy)
14	N	Orange	x				x	In den Obstsalat gehört auch eine ...	In the fruit salad also belongs an ... (orange)
15	N	Bus	x				x	Beeil dich, wir kommen zu spät zum ...	Hurry up. We'll be late for the ... (bus)
16	N	Lot	x				x	Die Mauer muss nach dem … ausgerichtet werden.	The wall must be aligned according to the ... (plumb line).
17	V	abmessen	x	x		x		Mit dem Lineal kann man Längen ...	With the ruler, you can … length (measure)
18	V	stoppen	x	x				Beim 100 m Lauf muss man die Zeit ...	At the 100 m run you have to … the time (measure)
19	V	schnappt	x	x				Der Fisch ... nach dem Haken.	The fish ... at the hook. (snaps)
20	V	heißen	x					Die Brüder ... Max und Moritz.	The brothers ... Max and Moritz. (are called)
21	V	erfahren	x		x			Die Nachricht ist unglaublich, Sarah muss unbedingt davon …	The news is unbelievable; Sarah has to … about it. (hear)
22	V	treffen	x	x				Können wir uns in der Pause auf dem Hof …?	Can we … in the yard during the break? (meet)
23	V	verschmutzen	x	x				Beim Essen ... kleine Kinder oft die Kleider.	While eating, small children often … their clothes (dirty).
24	V	mahlt	x		x			Die Mühlsteine drehen sich, wenn der Müller das Korn ...	The millstones turn when the miller … the grain (grinds)
25	V	bitten	x	x				Wenn die Gäste klingeln, ... wir sie herein.	When the guests ring the bell, we'll … them (invite).
26	A	verwöhnt	x		x			Meine Schwester ist ein Nesthäkchen, sie wird meistens ...	My sister is a nestling. She is mostly … (spoiled)
27	A	dick	x	x				Ein Buch mit 800 Seiten ist ...	A book with 800 pages is … (thick)
28	A	hässlich	x	x				Manche finden das Kunstwerk schön, andere finden es ...	Some find the work of art beautiful; others find it …(ugly)
29	A	schmierig	x			x		Wenn man zu viel Gel nimmt, werden die Haare oft ...	If you take too much gel, your hair often becomes … (greasy)
30	A	knurrend	x	x		x		Ich traute mich nicht ins Haus, weil ein Hund ... vor der Türe saß.	I didn't dare to go inside because a … dog was at the door. (growling)
31	A	plötzlich	x	x				Gerade hat die Sonne geschienen, jetzt fängt es ... an zu regnen.	The sun has just shone, now it … starts to rain (suddenly)
32	A	schneller	x	x				Mein neues Auto fährt ... als das alte.	My new car drives … than the old one. (faster)
33	A	hell	x	x				Die Sonne scheint ...	The sun is shining … (brightly)
34	A	okay	x				x	Den neuen Kinofilm findet Max ganz ...	Max finds the new movie quite … (okay)

Note: The test words were preceded by two practice trials (P). The Category (CAT.) column specifies if the test word was used as a noun, verb, or adjective in the sentence.

Table A3: Pseudowords: item set A and B.

	N	Cat.	Test word	CAP	COD	LEN	DEV	RULE	Sentence	English translation
Set A	P1	N	Ponu	x				NA	Auf dem Tisch stehen noch drei Tassen …	There are three cups… left on the table. (Ponu)
	P2	V	ralt	x				NA	Nach der Schule ... Paula gern.	After school Paula likes … (ralt)
	1	N	Mieb	x		x	x	NA	Auf der Wiese steht ein großes ...	On the meadow there is a large … (Mieb)
	2	N	Folb	x			x	NA	Wenn du einkaufen gehst, denke bitte an den ...	When you go shopping, please think of the … (Folb)
	3	N	Nabo	x				NA	Im Laden sah sie einen wunderschönen …	In the shop she saw a beautiful … (Nabo)
	4	N	Sprief	x		x		NA	Karla machte sich auf die Suche nach dem ...	Karla went on a search for the … (Sprief)
	5	N	Frabu	x				NA	Gestern Abend sah ich auf dem Dach einen …	Last night I saw a … on the roof. (Frabu)
	6	N	Tokale	x				NA	In Julias Vitrine stehen viele glänzende ...	In Julia's vitrine are many shiny … (Tokale)
	7	N	Mippokur	x	x			NA	Das ... ist ein riesiges Ungeheuer	The … is a huge monster. (Mippokur)
	8	N	Abworken	x			x	NA	Das ... bei der Klassenarbeit, ist nicht erlaubt.	The … for the class test is not allowed. (Abworken)
	9	N	Nulfen	x				NA	Ohne viel … kannst du nicht besser werden.	You can't get any better without a lot of … (Nulfen).
	10	V	flappern	x	x			NA	Stör mich nicht, ich muss etwas mit ihm ...	Don't bother me, I need to … to him a little. (flappern)
	11	V	nehlt	x		x		NA	Die Jungen warten gespannt, dass der Ball ...	The boys are eagerly waiting for the ball to … (nehlt)
	12	V	lampfen	x				NA	Warte auf mich, ich kann nicht so schnell ... !	Wait for me, I can't … that fast. (lampfen)
	13	V	krulst	x				NA	Ich kann mich nicht konzentrieren, wenn du so ...	I can't concentrate when you're so … (krulst)
	14	V	klompern	x				NA	Es lohnt sich, bei dem neuen Spiel zu ...	It's worth … on the new game. (klompern)
	15	V	geflochen	x				NA	Um Wasser zu sammeln, ... wir ein Regenfass.	To collect water, we … a rain barrel. (geflochen)
	16	V	stiezeln	x		x		NA	Es nervt ihn, wenn die Uhren zu laut. ____.	It annoys him when the clocks … too loud (stiezeln)
	17	A	boff	x	x			NA	Der große Korb war schnell ...	The big basket was fast … (boff))
	18	A	batull	x	x			NA	Ich will das nicht lesen, es ist viel zu ...!	I don't want to read this, it's too … (batull)
	19	A	schwelz	x				NA	Heute fühle ich mich zu ... zum Lernen.	Today I feel too … to learn (schwelz)
	20	A	strimsig	x			x	NA	Die Brücke ist morsch und ...	The bridge is rotten and… (strimsig)
Set B	P1	N	Laba	x				NA	Zum Kochen braucht Mama zwei Löffel ...	Mama needs two spoons to cook … (Laba)
	P2	V	fahlt	x		x		NA	Markus sitzt seit Stunden am Tisch und ...	Markus has been sitting at the table and … for hours. (fahlt)
	1	N	Birp	x			x	NA	Lass bloß die Finger von dem ...!	Don`t touch the … (Birp).
	2	N	Wirda	x				NA	Wenn man oben auf dem Berg steht, kann man den ... sehen.	On top of the mountain, you can see the … (Wirda)
	3	N	Schworg	x			x	NA	Ich kann nicht glauben, dass du auf den ... hereingefallen bist.	I can't believe you were tricked by the … (Schworg)
	4	N	Prone	x				NA	Nachher holt sie beim Nachbarn ihre ... ab.	Afterwards she picks up her … at the neighbour's. (Prone)
	5	N	Medale	x				NA	In Leons Buch gibt es nur wenige ...	There are only a few … in Leon's book. (Medale)
	6	N	Bammogen	x	x			NA	Das ... hat sechs kurze Beine.	The … has six short legs. (Mippokur)
	7	N	Serg	x				NA	Im Wasser schwimmt ein schneller ...	In the water swims a fast … (Serg)
	8	N	Abmerfen	X			x	NA	Das ... der Tür, ist nicht gestattet.	The … of the door is not permitted. (Abmerfen)
	9	N	Lonken	x				NA	Mit fleißigem ... kannst du die Klassenarbeit schaffen.	With diligent … you can finish the class test. (Nulfen)
	10	V	spoppen	x	x			NA	Warte bitte, ich muss noch etwas mit dir...	Please wait, I have something to … to you about. (spoppen)
	11	V	luhmt	x		x		NA	Keiner hätte geglaubt, dass er so lange ...	No one would've believed he'd be so long … (luhmt)
	12	V	lompern	x				NA	Man hörte die Reisegruppe laut johlen und ...	You could hear the travel group screaming loudly and … (lompern)
	13	V	nalcht	x				NA	Peter hat einen Freund, der sehr laut ...	Peter has a friend who is very loud … (nalcht)
	14	V	krolpen	x				NA	Es macht Spaß, mit Geschrei in die Pfützen zu ...	It's fun to … into the puddles … (krolpen)
	15	V	strohmpig	x		x	x	NA	Das Auto ist alt und ...	The car is old and … (strohmpig)
	16	V	geplauchen	x				NA	Wovon du redest, ... wir wirklich nicht.	What you're talking about, we really don't... (geplauchen)
	17	A	humm	x	x			NA	Die dunkle Höhle zu durchwandern, ist ...	Walking through the dark cave is … (hum)
	18	A	namoll	x	x			NA	Der Bischof wirkte in seinem Gewand sehr ...	The bishop was very … in his robe. (namoll)
	19	A	schnolz	x				NA	Herr Maiers Tag im Büro war heute sehr ...	Mr. Maier's office day was very … (schnolz)
	20	A	stiezen	x		x		NA	Sie ist gut gelaunt, wenn die Kinder ...	She is in a good mood if the children … (stiezen)

Note: The test words were preceded by two practice trials (P). The Category (CAT.) column specifies if the test word was used as a noun, verb, or adjective in the sentence.

APPENDIX B

APPENDIX B provides test material for the Copy task.

Table B1. Parallelized texts for the Copy Task in German

Text A:	**Text B:**
Bello und die Eisenbahn	Wuffi und der Rasenmäher
Die Mutter bittet ihren Sohn Felix, jetzt mit Bello raus zu gehen.	Die Mutter bittet ihren Sohn Lukas, jetzt den Rasen zu mähen.
Aber Felix hat überhaupt keine Lust. Er will lieber mit seiner neuen Eisenbahn spielen. Und was macht Bello? Der arme Hund sitzt mit seiner Leine ungeduldig vor der Tür und wartet.	Aber Lukas hat überhaupt keine Lust. Er will lieber mit seinem neuen Fußball spielen. Da kommt sein treuer Hund Wuffi in den Garten. Er setzt sich und wedelt freudig mit seinem Schwanz.

APPENDIX C

Appendix C summarizes the model selection procedure of the holistic approach.

Table C1: Model selection procedure using likelihood ratio tests.

		DF	AIC	BIC	*Loglik*	*Deviance*	*Chi²(DF)*	*p*
A)	**Spelling accurcy**	**DF**	**AIC**	**BIC**	***Loglik***	***Deviance***	***Chi²(DF)***	***p***
	null model	3	5491.4	5511.3	-2742.7	5485.4	NA	<.001
	Group	4	5459.56	5486.09	-2725.78	5451.56	33.84 (1)	<.001
	Group + Lex	5	5451.42	5484.59	-2720.71	5441.42	10.13 (1)	.03
	Group + Lex + Mode	**6**	**5448.64**	**5488.44**	**-2718.32**	**5436.64**	**4.79 (1)**	**.14**
	Group * Lex + Mode	7	5448.46	5494.89	-2717.23	5434.46	2.18 (1)	.31
	Group * Lex * Mode	10	5450.86	5517.19	-2715.43	5430.86	3.60 (3)	<.001
	Group + Lex + Mode	6	5448.6	5488.44	-2718	5437	NA	NA
	Sex + Group + Lex + Mode	7	5443.8	5490.23	-2715	5430	6.84 (1)	.01
	Sex + Age + Group + Lex + Mode	**8**	**5439.9**	**5492.99**	**-2712**	**5424**	**5.87 (1)**	**.02**
	Sex * Age + Group + Lex + Mode	9	5438.7	5498.37	-2710	5421	3.25 (1)	.07
	Sex * Age * Group + Lex + Mode	12	5442.4	5522.01	-2709	5418	2.26 (3)	.52
	Sex * Age * Group * Lex + Mode	19	5446.9	5572.98	-2704	5409	9.46 (7)	.22
	Sex * Age * Group * Lex * Mode	34	5456.7	5682.23	-2694	5389	20.20 (15)	.16
B)	**Self-Corrections**							
	null model	3	4032.04	4051.94	-2013.02	4026.04	NA	NA
	Mode	4	3876.70	3903.23	-1934.35	3868.70	157.35 (1)	<.001
	Mode + Group	5	3870.36	3903.53	-1930.18	3860.36	8.34 (1)	<.001
	Mode * Group	6	3850.82	3890.62	-1919.41	3838.82	21.54 (1)	<.001
	Mode * Group + Lex	**7**	**3842.84**	**3889.27**	**-1914.42**	**3828.84**	**9.98** (1)	**<.001**
	Mode * Lex * Group	10	3845.47	3911.80	-1912.73	3825.47	3.38(3)	.34
	Mode * Group + Lex	7	3842.84	3889.27	-1914.42	3828.84	NA	NA
	Age * Mode * Group + Lex	**11**	**3843.07**	**3916.04**	**-1910.53**	**3821.07**	**6.71 (1)**	**.01**
	Sex + Age * Mode * Group + Lex	10	3847.78	3914.11	-1913.89	3827.78	0.38 (1)	.54
	Sex + Age * Mode * Group * Lex	12	3844.37	3923.97	-1910.18	3820.37	0.70 (1)	.40
	Sex * Age * Mode * Group * Lex	34	3855.87	4081.40	-1893.93	3787.87	32.50 (22)	.07
C)	**Writing times**							
	CopyTime + Read	7	83828.30	83874.69	-41907.15	83814.30	NA	NA
	CopyTime + Read + Mode	8	83830.29	83883.31	-41907.14	83814.29	0.01 (1)	.92
	CopyTime + Read + Mode + Lex	9	83819.88	83879.52	-41900.94	83801.88	12.41 (1)	<.001
	CopyTime + Read + Mode * Lex	10	83821.39	83887.66	-41900.69	83801.39	0.49 (1)	.48
	CopyTime + Read + Mode * Lex + Group	11	83822.08	83894.98	-41900.04	83800.08	1.30 (1)	.25
	CopyTime + Read + Mode * Lex * Group	**13**	**83814.24**	**83900.39**	**-41894.12**	**83788.24**	**11.84 (2)**	**<.001**
	CopyTime + Read + Mode * Lex * Group	13	83814.24	83900.39	-41894.12	83788.24	NA	NA
	[…] Age * Mode * Lex * Group	**20**	**83675.66**	**83808.21**	**-41817.83**	**83635.66**	**152.58 (7)**	**<.001**
	[…] + Sex + Age * Mode * Lex * Group	22	83675.80	83821.60	-41815.90	83631.80	3.86 (2)	.14
	[…] + Sex * Age * Mode * Lex * Group	37	83621.60	83866.81	-41773.80	83547.60	84.20 (15)	<.001

Note: The hierarchically nested models were tested against the null model (with a random effect for subjects and items only) using likelihood ratio tests. The models included age and lexicality (Lex) as covariates.

APPENDIX D

Appendix D summarizes the model selection procedure for the rule-specific approach

Table D1: Capitalization: model selection procedure.

A)	**Spelling accurcy**	**DF**	**AIC**	**BIC**	***Loglik***	***Deviance***	***Chi*^{2}*(DF)***	***P***
	null model	3	3056.01	3075.91	-1525.01	3050.01	NA	NA
	Group	4	3046.83	3073.36	-1519.41	3038.83	11.19 (1)	<.001
	Group + Lex	5	3041.7	3074.86	-1515.85	3031.7	7.13 (1)	.01
	Group + Lex + WoCl	6	2947.2	2987	-1467.6	2935.2	96.50 (1)	<.001
	Group + Lex + WoCl + Mode	7	2946.25	2992.68	-1466.12	2932.25	2.95 (1)	.09
	Group + Lex + WoCl * Mode	8	2933.91	2986.98	-1458.96	2917.91	14.34 (1)	<.001
	Group + Lex * WoCl * Mode	***11***	***2927.4***	***3000.37***	***-1452.7***	***2905.4***	***12.51 (3)***	***.01***
	Group * Lex * WoCl * Mode	18	2933.23	3052.63	-1448.62	2897.23	8.17 (7)	.32
	Age + Group + Lex * WoCl * Mode	11	2927.4	3000.37	-1452.7	2905.4	NA	NA
	Sex + Age + Group + Lex * WoCl * Mode	12	2928.25	3007.85	-1452.12	2904.25	1.15 (2)	.28
	*Sex + Age + Group * Lex * WoCl * Mode*	*13*	*2926.19*	*3012.43*	*-1450.1*	*2900.19*	*4.05* (1)	*.04*
	Sex + Age * Group * Lex * WoCl * Mode	20	2932.35	3065.01	-1446.17	2892.35	7.85 (1)	.35
	Sex * Age * Group * Lex * WoCl * Mode	**66**	**2941.11**	**3378.92**	**-1404.56**	**2809.11**	**45.57** (3)	**.04**
B)	**Self-Corrections**							
	null model	3	1121.44	1141.34	-557.72	1115.44	NA	NA
	WoCl	4	1074.18	1100.71	-533.09	1066.18	49.26 (1)	<.001
	WoCl + Mode	5	1052.17	1085.35	-521.09	1042.17	24.00 (1)	<.001
	WoCl + Mode + Lex	**6**	**1048.67**	**1088.47**	**-518.33**	**1036.67**	**5.51 (1)**	**.02**
	WoCl + Mode + Lex + Group	7	1047.21	1093.66	-516.61	1033.21	3.45 (1)	.06
	WoCl * Mode + Lex + Group	8	1046.85	1099.93	-515.42	1030.85	2.36 (1)	.12
	WoCl * Mode * Lex + Group	11	1050.48	1123.46	-514.24	1028.48	2.37 (3)	.50
	WoCl * Mode * Lex * Group	18	1052.72	1172.14	-508.36	1016.72	11.77 (7)	.11
	WoCl + Mode + Lex	6	1048.67	1088.47	-518.33	1036.67	NA	NA
	Age + WoCl + Mode + Lex	7	1048.13	1094.58	-517.07	1034.13	2.53 (1)	.11
	Age + Sex + WoCl + Mode + Lex	8	1050.04	1103.11	-517.02	1034.04	0.10 (1)	.75
	Age * Sex + WoCl + Mode + Lex	9	1051.68	1111.40	-516.84	1033.68	0.35 (1)	.55
	Age * Sex *WoCl + Mode + Lex	12	1054.96	1134.58	-515.48	1030.96	2.72 (3)	.44
	Age * Sex *WoCl * Mode + Lex	19	1060.68	1186.74	-511.34	1022.68	8.28 (7)	.31
	Age * Sex *WoCl * Mode * Lex	34	1078.52	1304.10	-505.26	1010.52	12.16 (15)	.67
C)	**Writing Times**							
	CopyTime + Read	6	88062.22	88102.00	-44025.11	88050.22	NA	NA
	CopyTime + Read + Mode	7	87558.98	87605.38	-43772.49	87544.98	505.25 (1)	<.001
	CopyTime + Read + Mode + WoCl	8	87560.25	87613.28	-43772.12	87544.25	0.73 (1)	.39
	CopyTime + Read + Mode * WoCl	9	87547.53	87607.18	-43764.76	87529.53	14.72 (1)	<.001
	CopyTime + Read + Mode * WoCl + Lex	10	87548.83	87615.12	-43764.41	87528.83	0.70 (1)	.40
	CopyTime + Read + Mode * WoCl + Mode * Lex	**11**	**87542.11**	**87615.03**	**-43760.06**	**87520.11**	**8.72 (2)**	**<.001**
	CopyTime + Read + Mode * WoCl * Lex	13	87541.38	87627.55	-43757.69	87515.38	4.73 (8)	.09
	CopyTime + Read + Mode * WoCl + Mode * Lex	11	87542.11	87615.03	-43760.06	87520.11	NA	NA
	[…] + Age * Mode * WoCl + Mode * Lex	**15**	**87450.08**	**87549.51**	**-43710.04**	**87420.08**	**100.03 (4)**	**<.001**
	[…] + Sex + Age + Mode * WoCl + Mode * Lex	23	87461.11	87613.57	-43707.56	87415.11	4.97 (8)	.76
	[…] + Sex * Age + Mode * WoCl + Mode * Lex	37	87472.34	87717.60	-43699.17	87398.34	16.77 (14)	.27

Note: The hierarchically nested models were tested against the null model (with a random effect for subjects and items only) using likelihood ratio tests. The models included age and lexicality (Lex) as covariates.

Table D2: Consonant doubling: Model selection procedure.

A)	Spelling accuracy	DF	AIC	BIC	*Loglik*	*Deviance*	*Chi²(DF)*	*P*
	null model	3	1430.83	1447.67	-712.41	1424.83	NA	NA
	Group	4	1405.73	1428.19	-698.86	1397.73	27.10 (1)	<.001
	Group + Lex	**5**	**1387.00**	**1415.08**	**-688.50**	**1377.00**	**20.73 (1)**	**<.001**
	Group * Lex	6	1389.00	1422.69	-688.50	1377.00	0.00 (1)	.98
	Group + Lex	5	1387.00	1415.08	-688.50	1377.00	NA	NA
	Sex + Group + Lex	6	1381.83	1415.52	-684.92	1369.83	7.17 (1)	.01
	Sex + Age + Group + Lex	**7**	**1375.84**	**1415.14**	**-680.92**	**1361.84**	**8.00 (1)**	**<.001**
	Sex + Age * Group * Lex *	11	1382.47	1444.24	-680.24	1360.47	1.37 (4)	.85
	Sex * Age * Group * Lex *	18	1383.18	1484.26	-673.59	1347.18	13.29 (7)	.07
B)	**Self-Corrections**							
	null model	3	333.68	350.53	-163.84	327.68	NA	NA
	Mode	**4**	**330.78**	**353.25**	**-161.39**	**322.78**	**4.90 (1)**	**.03**
	Mode + Group	5	330.82	358.90	-160.41	320.82	1.97 (1)	.16
	Mode * Group	6	331.68	365.38	-159.84	319.68	1.14 (1)	.29
	Mode	4	330.78	353.25	-161.39	322.78	NA	NA
	Age + Mode	5	332.68	360.77	-161.34	322.68	0.10 (1)	.75
	Age + Sex + Mode	6	332.71	366.40	-160.35	320.71	1.98 (1)	.16
	Age * Sex + Mode	7	331.25	370.56	-158.62	317.25	3.46 (1)	.06
	Age * Sex * Mode	10	332.95	389.11	-156.48	312.95	4.30 (1)	.23
C)	**Writing times**							
	CopyTime + Read	6	29711.92	29745.57	-14849.96	29699.92	NA	NA
	CopyTime + Read + Mode	7	29712.70	29751.96	-14849.35	29698.70	1.22 (1)	.27
	CopyTime + Read + Mode + Lex	**8**	**29444.68**	**29489.54**	**-14714.34**	**29428.68**	**270.03 (1)**	**<.001**
	CopyTime + Read + Mode * Lex	9	29446.50	29496.96	-14714.25	29428.50	0.18 (1)	.67
	CopyTime + Read + Mode * Lex + Group	10	29445.80	29501.87	-14712.90	29425.80	2.70 (1)	.10
	CopyTime + Read + Mode * Lex + Group * Lex	11	29447.80	29509.48	-14712.90	29425.80	0.00 (1)	.98
	CopyTime + Read + Mode * Lex * Group	13	29445.93	29518.83	-14709.97	29419.93	5.87 (2)	.06
	CopyTime + Read + Mode + Lex	8	29444.68	29489.54	-14714.34	29428.68	NA	NA
	CopyTime + Read + Age + Mode + Lex	9	29432.99	29483.45	-14707.49	29414.99	13.69 (1)	<.001
	CopyTime + Read + Age * Mode + Lex	**10**	**29385.54**	**29441.61**	**-14682.77**	**29365.54**	**49.44** (1)	**<.001**
	CopyTime + Read + Age * Mode + Lex	12	29386.47	29453.76	-14681.23	29362.47	3.07 (2)	.22
	CopyTime + Read + Age * Mode + Age * Lex	14	29386.89	29465.39	-14679.44	29358.89	3.58 (2)	.17
	CopyTime + Read + Age * Mode * Lex	21	29395.65	29513.40	-14676.82	29353.65	5.24 (7)	.63

Note: The hierarchically nested models were tested against the null model (with a random effect for subjects and items only) using likelihood ratio tests. The models included age and lexicality (Lex) as covariates.

Table D3: Lengthening: Model selection procedure

A)	Spelling accuracy	DF	AIC	BIC	*Loglik*	*Deviance*	*Chi²(DF)*	*p*
	null model	3	846.22	861.06	-420.11	840.22	NA	NA
	Group	4	807.79	827.57	-399.89	799.79	40.44 (1)	<.001
	Group + Lex	5	793.17	817.90	-391.58	783.17	16.62 (1)	<.001
	Group * Lex	**6**	**783.98**	**813.66**	**-385.99**	**771.98**	**11.19** (1)	**<.001**
	Group * Lex + Mode	7	785.47	820.10	-385.73	771.47	0.51 (1)	.48
	Group * Lex * Mode	10	790.12	839.59	-385.06	770.12	1.35 (3)	0.72
	Group * Lex	5	793.17	817.90	-391.58	783.17	NA	NA
	Sex + Group * Lex	7	780.63	815.26	-383.31	766.63	16.54 (2)	<.001
	Sex + Age + Group * Lex	**8**	**773.99**	**813.57**	**-379.00**	**757.99**	**8.63 (3)**	**<.001**
	Sex + Age * Group * Lex	11	776.40	830.82	-377.20	754.40	3.59 (1)	.31
	Sex * Age * Group * Lex	18	781.73	870.78	-372.87	745.73	8.67 (7)	.28
B)	**Self-Corrections**							
	null model	3	177.67	192.44	-85.83	171.67	NA	NA
	Mode	**4**	**163.80**	**183.50**	**-77.90**	**155.80**	**15.87 (1)**	**<.001**
	Mode + Group	5	164.70	189.33	-77.35	154.70	1.10 (1)	.30
	Mode * Group	6	166.04	195.60	-77.02	154.04	0.66 (1)	.42
	Mode	4	163.80	183.50	-77.90	155.80	NA	NA
	Age + Mode	5	165.34	189.97	-77.67	155.34	0.46 (1)	.50
	Age + Sex + Mode	6	167.23	196.79	-77.62	155.23	0.11 (1)	.75
	Age * Sex + Mode	7	168.83	203.31	-77.41	154.83	0.41 (1)	.52
	Age * Sex * Mode	10	172.74	222.00	-76.37	152.74	2.08 (3)	.56
C)	**Writing times**							
	CopyTime + Read	6	16135.26	16164.90	-8061.63	16123.26	NA	NA
	CopyTime + Read + Mode	**7**	**16023.88**	**16058.46**	**-8004.94**	**16009.88**	**113.38** (1)	**<.001**
	CopyTime + Read + Mode + Lex	8	16024.71	16064.23	-8004.36	16008.71	1.17 (1)	.28
	CopyTime + Read + Mode * Lex	9	16026.29	16070.76	-8004.15	16008.29	0.42 (1)	.52
	CopyTime + Read + Mode * Lex + Group	10	16027.37	16076.78	-8003.69	16007.37	0.92 (1)	.34
	CopyTime + Read + Mode * Lex * Group	13	16033.09	16097.31	-8003.55	16007.09	0.28 (2)	.96
	CopyTime + Read + Mode	7	16023.88	16058.46	-8004.94	16009.88	NA	NA
	CopyTime + Read + Age * Mode	**9**	**16002.12**	**16046.58**	**-7992.06**	**15984.12**	**25.76 (2)**	**<.001**
	CopyTime + Read + Sex + Age * Mode	10	16001.96	16051.36	-7990.98	15981.96	2.16 (1)	.14
	CopyTime + Read + Sex * Age * Mode	13	16007.52	16071.75	-7990.76	15981.52	0.43 (3)	.93

Note: The hierarchically nested models were tested against the null model (with a random effect for subjects and items only) using likelihood ratio tests. The models included age and lexicality (Lex) as covariates.

Table D4: Devoicing: Model selection procedure.

A)	Spelling accuracy	DF	AIC	BIC	*Loglik*	*Deviance*	*Chi²(DF)*	*p*
	null model	3	387.02	401.00	-190.51	381.02	NA	NA
	Group	4	374.95	393.58	-183.47	366.95	14.07 (1)	<.001
	Group + Lex	5	376.89	400.19	-183.45	366.89	0.05 (1)	.82
	Group * Lex	**6**	**375.30**	**403.26**	**-181.65**	**363.30**	**3.59 (1)**	**.05**
	Group * Lex + Mode	7	375.93	408.55	-180.97	361.93	1.37 (1)	.24
	Group * Lex * Mode	10	377.36	423.95	-178.68	357.36	4.57 (1)	.21
	Group * Lex	5	376.89	400.19	-183.45	366.89	NA	NA
	Sex + Group * Lex	7	376.71	409.33	-181.36	362.71	4.18 (2)	.12
	Sex + Age + Group * Lex	8	378.67	415.94	-181.33	362.67	0.05 (1)	.83
	Sex + Age * Group * Lex	11	384.40	435.65	-181.20	362.40	0.27 (3)	.97
	Sex * Age * Group * Lex	18	393.65	477.52	-178.83	357.65	4.75 (7)	.69
B)	**Self-Corrections**							
	null model	3	70.42	84.35	-32.21	64.42	NA	NA
	Mode	4	72.42	90.99	-32.21	64.42	0.00 (1)	.96
	Mode + Group	5	74.43	97.65	-32.22	64.43	0.00 (1)	1.00
	Mode * Group	**6**	**71.44**	**99.30**	**-29.72**	**59.44**	**4.99** (1)	**.03**
	Mode * Group	6	71.44	99.30	-29.72	59.44	4.98 (1)	.17
	Sex + Mode * Group	7	74.04	106.54	-30.02	60.04	0.00 (1)	1.00
	Sex * Mode * Group	**10**	**67.93**	**114.36**	**-23.97**	**47.93**	**11.51** (4)	**.02**
	Age + Sex * Mode * Group	11	69.95	121.02	-23.98	47.95	0.00 (1)	1.00
	Age * Sex * Mode * Group	18	89.28	172.84	-26.64	53.28	0.00 (7)	1.00
C)	**Writing times**							
	CopyTime + Read	6	11569.47	11597.42	-5778.73	11557.47	NA	NA
	CopyTime + Read + Mode	**7**	**11440.48**	**11473.10**	**-5713.24**	**11426.48**	**130.98 (1)**	**<.001**
	CopyTime + Read + Mode + Lex	8	11441.61	11478.89	-5712.81	11425.61	0.87 (1)	.35
	CopyTime + Read + Mode + Lex + Group	9	11443.50	11485.43	-5712.75	11425.50	0.11 (1)	.73
	CopyTime + Read + Mode * Lex + Group	10	11444.43	11491.03	-5712.22	11424.43	1.06 (1)	.30
	CopyTime + Read + Mode * Lex * Group	13	11447.79	11508.36	-5710.90	11421.79	2.64 (3)	.45
	CopyTime + Read + Mode	7	11440.48	11473.10	-5713.24	11426.48	NA	NA
	CopyTime + Read + Age * Mode	**9**	**11410.29**	**11452.22**	**-5696.14**	**11392.29**	**34.20 (2)**	**<.001**
	CopyTime + Read + Sex + Age * Mode	10	11411.07	11457.67	-5695.54	11391.07	1.21 (1)	.27
	CopyTime + Read + Sex + Age * Mode	13	11415.90	11476.47	-5694.95	11389.90	1.18 (3)	.76

Note: The hierarchically nested models were tested against the null model (with a random effect for subjects and items only) using likelihood ratio tests. The models included age and lexicality (Lex) as covariates.

Table D5: Rule words: Model selection procedure.

A)	Spelling accuracy	DF	AIC	BIC	*Loglik*	*Deviance*	*Chi²(DF)*	*p*
	null model	3	865.41	879.58	-429.70	859.41	NA	NA
	Group	**4**	**854.73**	**873.63**	**-423.37**	**846.73**	**12.68 (1)**	**<.001**
	Group + Mode	5	856.70	880.32	-423.35	846.70	0.03 (1)	.85
	Group * Mode	6	858.19	886.53	-423.09	846.19	0.51 (1)	.48
	Group * Mode	4	854.73	873.63	-423.37	846.73	NA	NA
	Sex + Group * Mode	**5**	**854.71**	**878.33**	**-422.36**	**844.71**	**2.02** (1)	**<.001**
	*Sex + Age + Group * Mode*	6	852.16	880.50	-420.08	840.16	4.55 (1)	.85
	*Sex + Age * Group * Mode*	10	853.85	901.09	-416.93	833.85	6.10 (3)	.11
B)	**Self-Corrections**							
	null model	3	329.23	343.36	-161.62	323.23	NA	NA
	Mode	**4**	**322.71**	**341.55**	**-157.36**	**314.71**	**8.52** (1)	**<.001**
	Mode + Group	5	324.57	348.11	-157.28	314.57	0.15 (1)	.70
	Mode * Group	6	326.40	354.65	-157.20	314.40	0.17 (1)	.68
	Mode	4	322.71	341.55	-157.36	314.71	NA	NA
	Age + Mode	5	324.14	347.68	-157.07	314.14	0.58 (1)	.45
	Age * Mode	6	325.17	353.42	-156.58	313.17	0.97 (1)	.33
	Sex + Age * Mode	**7**	**323.27**	**356.23**	**-154.64**	**309.27**	**3.90** (1)	**.05**
	Sex * Age * Mode	10	326.68	373.76	-153.34	306.68	2.59 (3)	.46
C)	**Writing times**							
	CopyTime + Read	6	13232.35	13260.66	-6610.18	13220.35	NA	NA
	CopyTime + Read + Mode	**7**	**13163.77**	**13196.80**	**-6574.89**	**13149.77**	**70.58 (1)**	**<.001**
	CopyTime + Read + Mode + Lex	9	13167.44	13209.90	-6574.72	13149.44	0.34 (2)	.84
	CopyTime + Read + Age + Mode	7	13163.77	13196.80	-6574.89	13149.77	NA	NA
	CopyTime + Read + Age * Mode	**9**	**13155.77**	**13198.23**	**-6568.88**	**13137.77**	**12.01 (2)**	**<.001**
	CopyTime + Read + Sex + Age * Mode	10	13155.10	13202.28	-6567.55	13135.10	2.66 (1)	.10
	CopyTime + Read + Sex * Age * Mode	13	13155.38	13216.72	-6564.69	13129.38	5.72 (3)	.13

Note: The hierarchically nested models were tested against the null model (with a random effect for subjects and items only) using likelihood ratio tests. The models included age and lexicality (Lex) as covariates.