

Double-letter processing in developmental and skilled handwriting production: Evidence from kinematics

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Abstract

In this study, we investigated the effects of double-letter processing on handwriting production in beginning and skilled writers of German. One hundred and thirty-seven children from Grades 2 and 3 and 31 adult participants were asked to copy words with double consonants (e.g., “Kanne”) and matched words without double consonants (e.g., “Kante”) from a computer screen onto a pen tablet, while their handwriting was recorded with high spatio-temporal resolution. Handwriting productions were analysed in terms of Reading Duration, Writing Onset Duration, and Letter Duration at the letter positions preceding or forming the onset of the corresponding consonant clusters. Our results showed that second graders take less time to initiate writing words with double consonants than words without double consonants, while both second and third graders take less time to read words with double consonants than words without double consonants. Critically, although second and third graders write down a letter faster when it corresponds to the first letter of a double-letter unit than a consonant cluster, it is the other way around for adults. We interpret these findings within extant theories of handwriting production and offer an explanation for the different nature of the effects observed in beginning and skilled writers.

Keywords

Handwriting production; spelling; double letters; kinematics

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Research on handwriting production using kinematic measures has flourished over the past few decades (e.g., Kandel et al., 2006; Meulenbroek & van Galen, 1988; Quémart & Lambert, 2019; Thomassen & Teulings, 1979; Zesiger et al., 1993). The available empirical evidence shows that writers change movement duration in the course of word production systematically, and that such changes are not exclusively due to motoric requirements induced by the shape of the letter to-be-written (e.g., Kandel et al., 2011; van Galen, 1991). Instead, it has been argued that higher level cognitive processes are not completed before motor production, but cascade all the way down to influence motor execution (e.g., Kandel & Perret, 2015; Roux et al., 2013). Indeed, changes in movement duration during handwriting often reflect orthographic and phonological influences on handwriting production (e.g., Afonso et al., 2015; Hess et al., 2019).

When learning to write, children come across orthographic, phonological, and morphological patterns of their

writing system (e.g., Treiman & Kessler, 2014). The handwriting production of such patterns poses a challenge for beginning writers. For example, syllable and morpheme boundaries (e.g., Hess et al., 2019; Kandel & Valdois, 2006; Quémart & Lambert, 2019), orthographic regularity (e.g., Kandel & Perret, 2015; Kandel & Valdois, 2005), as well as graphemic complexity (e.g., Kandel et al., 2006) are shown to affect movement duration during handwriting. Similarly,

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beginning writers of English (Cassar & Treiman, 1997) and French (Pacton et al., 2001; Pacton et al., 2013) have difficulties producing words containing double letters (e.g., Treiman & Kessler, 2014), even though they are taught that certain letters are doubled within specific word positions. Moreover, children are familiar with the presence of double letters in words from an early age. For example, in the Cassar and Treiman (1997) study, phonetic spellers, namely children that attempted to resemble the sound pattern of words in writing, were more likely to choose nonwords with allowable double letters (e.g., “yill”) over nonwords with unallowable double letters (e.g., “yihh”) as more word-like. Importantly, although double letters are common in most alphabetic languages, the available empirical evidence from effects of double-letter processing on handwriting production is scant.

To our knowledge, the only studies that investigated this issue have been conducted with skilled writers of Italian, French, Dutch, and English (Kandel et al., 2013, 2014, 2019; van Galen et al., 1989). In most of these studies, the data revealed that double-letter processing influences handwriting production before and during trajectory formation. For example, Italian writers took less time (Kandel et al., 2019) and French writers took more time (Kandel et al., 2014) to start writing words with double letters than words without double letters. Also, writers of Dutch produced the same letter (e.g., “o”) faster when it preceded a double-letter unit (e.g., “mm” in “ommers”) than a consonant cluster (e.g., “md” in “omdoen”; van Galen et al., 1989). Furthermore, writers of both Dutch and French produced the same letter (e.g., “m” or “s”) slower when it formed the first letter of a double-letter unit (e.g., “mm” in “ommers” or “ss” in “lisser”) than the first letter of a consonant cluster (e.g., “md” in “omdoen” or “st” in “lister”; Kandel et al., 2014; van Galen et al., 1989). The evidence from English was less clear, with no apparent influence of double-letter processing on handwriting production at the aforementioned positions (Kandel et al., 2019). Taken together, these results seem to be inconsistent across languages. Furthermore, the available empirical evidence is limited to data from skilled writers. In this study, we sought to investigate the influence of double-letter processing on handwriting production in a language that has not been previously investigated, that is, German. Furthermore, we conducted this study with both developing and skilled writers, while we recorded handwriting movements with high spatio-temporal resolution. Kinematic data are important, in so far as they allow us to track in real time the influence of higher levels of cognitive processing on handwriting production.

Double letters play a special role in the German language. For example, double consonants, such as “nn” in words like “Kanne” (pot; /kaɲə/, <kan.ne>, ¹ i.e., /CVČV/, <CVC.CV>), denote that the vowel preceding the double consonant is short (e.g., Eisenberg, 2013; Fuhrhop, 2009).

This orthographic characteristic is particularly useful for readers of German, because it indicates that closed full syllables, such as “Kan” in “Kan.ne” and “Kan.te” (edge; /kan.tə/, <kan.te>, i.e., /CVC.CV/, <CVC.CV>), contain short vowels, whereas open full syllables, such as “Ka” in “Ka.ter” (male cat; /ka.təʀ/, <ka.ter>, i.e., /CV.CVC/, <CV.CVC>), contain long vowels. Double consonants are more demanding in spelling than in reading. This is because there are German words that have a different orthographic form, yet the same phonological word form, such as “Mann” (*noun*, man; /man/, <mann>, i.e., /CVC/, <CVCC>) and “man” (*pronoun*, one; /man/, <man>, i.e., /CVC/, <CVC>). Also, multisyllabic word forms containing a double consonant, such as “Felle” (*plural*, furs; /fɛlə/, <fel.le>), maintain their double consonant in morphologically related monosyllabic word forms, such as “Fell” (*singular*, fur; /fɛl/, <fell>). In sum, double letters are very common in German and spelling of words containing double letters requires knowledge of both phonological and morphological patterns in the language. Perhaps for this reason, double letters are explicitly taught to beginning writers of German.

Understanding how double letters are processed during handwriting production is important for the further development of extant theories of handwriting production. According to these theories (van Galen et al., 1989; see also Teulings et al., 1983; van Galen, 1990, 1991), similarity of adjacent linguistic units such as syllables or double letters reduces short-term memory demands at the spelling level, thus facilitating activation and maintenance of orthographic representations in the orthographic buffer and retrieval of the individual letter units. Orthographic representations stored in the orthographic buffer are thought to be derived from phonological representations, while words with double letters are thought to contain a “double code” (van Galen et al., 1989). Orthographic representations are activated prior to word writing onset, while letter units are retrieved and substituted by an allograph (i.e., the motoric representation of a letter in a specific context, such as lower or upper case, cursive or printed script) during writing. According to van Galen et al. (1989), this occurs one letter position ahead of real-time trajectory formation. Therefore, the double “n” in “Kanne” (i.e., double code) and the single “n” in “Kante” would be retrieved and substituted by an allograph during the production of “a.” On the assumption that double letters are less demanding for short-term memory than consonant clusters (van Galen et al., 1989), “a” would be expected to be written faster in “Kanne” than in “Kante.”

However, it is worth noting that the mechanism via which orthographic representations of words with double letters are activated, as well as the mechanism for encoding double letters were underspecified in those early theories. For this reason, additional theories have been more recently developed to account for both mechanisms. For example,

according to the dual-route theory (e.g., Bonin et al., 2015; Miceli & Costa, 2014), orthographic representations of the words to-be-spelled (including words with double letters) are either accessed via a lexical route through mentally stored lexical representations for familiar words or assembled via a sublexical route by means of phonology-to-orthography conversion processes for unfamiliar words. Both routes are thought to be active in parallel and to interact during the determination of the final spelling (e.g., Rapp et al., 2002; Roux et al., 2013). Orthographic representations are then processed by an orthographic working memory component, known as “graphemic” or “orthographic buffer,” which maintains information active and ensures that letters are produced in a correct serial order (e.g., Miceli & Costa, 2014; Rapp et al., 2016). Then, with regard to the encoding mechanism, Caramazza and Miceli (1990; see also McCloskey et al., 1994; Tainturier & Caramazza, 1996) postulate that double letters are processed as a single letter unit, which is assigned a quantity feature indicating the number of repetitions (e.g., “n” in “Kanne” has a quantity feature indicating two repetitions). Importantly then, orthographic representations of words with double letters are shorter than words without double letters (e.g., “Kanne” has four letter units, whereas “Kante” has five letter units). On the assumption that shorter representations are less demanding for short-term memory than longer representations (see also van Galen et al., 1989), words with double letters would be expected to be processed faster than words without double letters. This prediction concerns the spelling level. However, additional predictions can be made by the available theories concerning other levels of representation (e.g., the motor level). We outline these predictions below.

On the assumption that similar adjacent letter units form a double code (van Galen et al., 1989), or are processed as a single letter unit (Caramazza & Miceli, 1990), handwriting production may become motorically more demanding for words with double letters than for words without double letters (e.g., van Galen, 1991; van Galen et al., 1989). This is because the motor level operates at grain sizes corresponding to strokes, once allographs have been selected, and requires both adjusting the overall force parameters for real-time performance of writing movements in an adequate size and speed, and recruitment of the appropriate muscle groups. This takes place during real-time trajectory formation of the actual letter. Importantly, similarity between strokes, as it is the case with double letters due to a double code, inhibits their retrieval from the motor buffer. As such, when a letter corresponds to the first letter of a double-letter unit (e.g., “n” in “Kanne”), it would be expected to be written more slowly than when it corresponds to the first letter of a consonant cluster (e.g., “n” in “Kante”; van Galen et al., 1989).

Although the predictions outlined above concern different representational levels (spelling vs. motor level), it is worth pointing out that the expected effects differ in nature.

In particular, facilitatory effects are expected at the spelling level and inhibitory effects are expected at the motor level. On the basis of van Galen’s (1991) model of handwritten language production, handwriting production comprises three processing levels prior to real-time trajectory formation: (a) a conceptual level, which consists of modules for the activation of intentions, semantic retrieval, and syntactic construction; (b) a spelling level; and (c) a motor level. These modules exhibit a hierarchical structure so that the output from each level forms the input to the next level. Crucially, even though processing along the modules occurs in a serial manner, so that information from the conceptual level cascades down to the spelling level, and subsequently to the motor level, all modules are thought to operate simultaneously. The sharing of limited cognitive processing resources between parallel higher- and lower-level processes may slow down real-time trajectory formation. On this assumption, double-letter processing should show both types of effects in real-time trajectory formation: Facilitatory effects at the spelling level should accelerate real-time trajectory formation prior to the double letter, while inhibitory effects at the motor level should decelerate it during the production of the double letter.

In this study, we tested these ideas by investigating effects of consonant doubling on handwritten word production in beginning and skilled writers of German. With regard to the spelling level, we hypothesised that writers would start writing words with double letters (e.g., “Kanne”) faster than words without double letters (e.g., “Kante”), because the former types of words consist of fewer distinct letters than the latter. For the same reason, writers should be faster writing down a letter that precedes a double-letter unit (e.g., “a” before “nn” in “Kanne”) than a letter that precedes a consonant cluster (e.g., “a” before “nt” in “Kante”). However, as far as the motor level is concerned, we hypothesised that writers would write a letter slower when it corresponds to the first letter of a double-letter unit (e.g., “n” in “Kanne”) than when it corresponds to the first letter of a consonant cluster (e.g., “n” in “Kante”). The latter hypothesis is based on the idea that similarity of strokes in the motor buffer is thought to slow down the production of similar letters (van Galen et al., 1989).

We tested 7- to 10-year-old German children from Mid-Grade 2 and Mid-Grade 3 and adults. Participants were asked to write down items with and without double letters (e.g., “Kanne” vs. “Kante”) while we recorded their handwritten productions with high spatio-temporal resolution. Children in these age groups were chosen because in Germany, Mid-Grade 2 appears to be the point in time when children are familiar with phonetic spelling but have not been explicitly taught how to spell words with double consonants. As such, second graders have not yet acquired a double code mechanism for double letters. Consequently, they should show neither facilitation at the spelling level nor inhibition at the motor level, because to them, the

number of letter units in words with and without double letters is identical. Explicit instruction is typically given between Mid-Grade 2 and Mid-Grade 3, hence Mid-Grade 3 is the point in time when children have been taught about consonant doubling and have been additionally exposed to print for another year. As such, we expected third graders to have acquired a double-code mechanism for double letters. On this assumption, children's writing behaviour in Grade 3 might be similar to adult writing behaviour. Skilled adult writers should show the predicted facilitatory and inhibitory effects at the spelling and motor level, respectively, and so should children in Grade 3.

Method

Participants

Sixty-nine children from Grade 2 and 68 children from Grade 3, recruited from 11 classes (seven in Grade 2 and four in Grade 3) of three state primary schools in Berlin, Germany, participated in the experiment for a small gift. A group of 31 adults also participated in the experiment for monetary reimbursement. Writing production data were incomplete for two children from Grade 2. Thus, these children were excluded from the study. As a result, a total of 67 children from Grade 2 (62 right-handed, three left-handed, two ambidextrous; 34 females), who were on average 8.0 years old ($SD = 0.3$, range = [7.3–8.8]), and 68 children from Grade 3 (58 right-handed, eight left-handed, two ambidextrous; 27 females), who were on average 8.8 years old ($SD = 0.5$, range = [7.2–10.2]), as well as 31 adults (25 right-handed, six left-handed; 20 females), who were on average 26.0 years old ($SD = 3.1$, range = [20.4–31.0]), were included in the analyses. All participants reported to have learned German before the age of 5.

The study was approved by the ethics committee of the Max Planck Institute for Human Development in Berlin, Germany, and by the Senate Department for Education, Youth, and Science of the federal state of Berlin, Germany. Adult participants gave written informed consent in accordance with the Declaration of Helsinki. Children gave oral consent, while written consent was obtained from their parents.

Materials

Forty nouns were selected as targets (see the Supplementary Material). Items were assigned to either of two conditions that manipulated consonant doubling at Bigram Position 3: no consonant-doubling (NoCD) condition and consonant-doubling (CD) condition (e.g., “nt” in “Kante” vs. “nn” in “Kanne”). In both conditions, items were either monosyllabic and four letters long or disyllabic and five letters long. Items of the NoCD condition comprised the same number of letters and sounds (i.e., <kan.te> and /kan.tə/).

Due to the double-consonant feature, items of the CD condition comprised one more letter than sounds (i.e., <kan.ne> and /kañə/).

Each of the 20 word pairs that were used in the study, such as “Zelt” (tent) and “Fell,” or “Kante” and “Kanne,” shared their target VC sequence at Bigram Position 2 (e.g., “el” in “Zelt” and “Fell,” or “an” in “Kante” and “Kanne”). Furthermore, whenever possible, item pairs shared their onset (see Supplementary Material). As a result, items were overall matched on logarithmically (\log_{10}) transformed position-specific unigram type frequency, $M_{\text{NoCD}} = 2.36$ versus $M_{\text{CD}} = 2.35$, $F(1,19) = 0.04$, $p = .849$, logarithmically (\log_{10}) transformed position-specific bigram type frequency, $M_{\text{NoCD}} = 1.56$ versus $M_{\text{CD}} = 1.56$, $F(1,19) = 0.05$, $p = .825$, and logarithmically (\log_{10}) transformed position-specific trigram type frequency, $M_{\text{NoCD}} = 0.63$ versus $M_{\text{CD}} = 0.62$, $F(1,19) = 0.08$, $p = .775$, at initial position, according to the childLex norms (Version 0.17.01; Schroeder et al., 2015). In addition, items were matched on logarithmically (\log_{10}) transformed position-specific unigram type frequency at the fourth position, $M_{\text{NoCD}} = 2.54$ versus $M_{\text{CD}} = 2.53$, $F(1,19) = 0.02$, $p = .877$, while both conditions were matched on logarithmically (\log_{10}) transformed normalised type frequency, $M_{\text{NoCD}} = 1.13$ versus $M_{\text{CD}} = 1.17$, $F(1,19) = 0.02$, $p = .893$, and orthographic Levenshtein distance 20 (OLD20; Yarkoni et al., 2008), $M_{\text{NoCD}} = 1.40$ versus $M_{\text{CD}} = 1.27$, $F(1,19) = 1.73$, $p = .204$, according to the childLex norms.

Procedure

Participants were tested individually in a quiet room, either at their school (children) or at the Max Planck Institute for Human Development in Berlin, Germany (adults). Each target word was presented in black 24-point Arial font on white background in the centre of a 24-in. monitor screen. An auditory signal and a blank screen preceded each trial for 1,000 ms (children) or 500 ms (adults). We opted for using a copy task because by providing participants the letter string to be written, the number of spelling errors is reduced, while the number of productions that can be compared across participants is increased (Lambert et al., 2012). This is particularly important for research with beginning writers who tend to make many spelling errors.

In contrast to previous real-time handwriting studies on double-letter processing, which used direct copy tasks (e.g., Kandel et al., 2014, 2019; van Galen et al., 1989), in which the printed stimulus remains present during handwriting production, we used a delayed copy task (e.g., Lambert et al., 2008; see also McCloskey et al., 1994; Tainturier & Caramazza, 1996), in which the printed stimulus is not present during handwriting production. In particular, the stimulus remained on the screen until participants read it and pressed the pen tip onto a blue trigger zone at the bottom right-handed corner of the tablet.

The screen remained then blank until participants produced their written response. A delayed copy task is typically used to ensure that writers visualise mentally the to-be-spelled stimulus prior to writing onset, thus making this task similar to offline writing tasks that are typically used with developmental writers (e.g., written object naming, spelling to dictation).

Participants first received a response sheet with 10 lines (horizontal length of a line 170 mm; vertical distance between lines 12.5 mm). They were then given a Wacom Intuos4 Inking Pen and were asked to write down the presented word on a new line for each trial. Participants were asked to perform the task accurately and to use their preferred script (i.e., printed or cursive) to ensure fluent motor production, which is particularly important for young children. Participants' response sheets were laid over a Wacom Intuos4 XL Tablet that was connected to an IBM-compatible laptop running Windows 7. Pen-tip position and pen-tip pressure were registered in real time (sampling rate 200 Hz; spatial resolution 100 lines/mm) and were controlled by *Ecriture* from the *Ductus* software package (Version 1.0.1.218; Guinet & Kandel, 2010).

Participants were familiarised with the pen and the writing surface by scribbling at the top of the response sheet and by writing down the word "Schule" (school) in response to dictation. Participants were presented with 40 experimental trials that appeared in random order, interspersed with 20 filler trials. Three practice trials preceded the experimental trials. After each trial, participants initiated the next trial by pressing onto the blue trigger zone at the bottom right-handed corner of the tablet. Participants were encouraged to take a break after half of the experimental trials were presented. A practice trial preceded the second half of the experimental trials. The experimenter replaced the response sheet with a new one after the practice trials and, subsequently, after every 10 experimental trials.

Analysis

For the analysis of the handwritten productions, each word was automatically filtered and manually segmented into its individual letters using *MarkWrite* from the *OpenHandWrite* software package (Version 0.3.2; Simpson et al., 2017). In those cases where participants (a) did not press the pen tip onto the blue trigger zone after reading the word, (b) gave an incorrect response or misspelled the word, or (c) corrected their response during the trial, data were treated as errors and discarded from the analysis (Grade 2: 24.1% of the data; Grade 3: 12.9%; adults: 5.7%). In case trials involved the letter "i" (e.g., "Rinde" or "Rinne"), the dot was only part of the letter if it was produced before the next letter. Trials involving "i" were pairwise excluded from the analysis if the dot was part of the letter in one condition but not in the other (Grade 2: 2.1% of the data; Grade 3: 1.5%; adults: 1.2%).

This procedure ensured that differences in movement duration between conditions could not be attributed to differences in trajectory length between conditions.

Reading Duration, Writing Onset Duration, and Letter Duration at Letter Positions 2 (i.e., vowel preceding consonant cluster) and 3 (i.e., onset of consonant cluster) were calculated for the target words and used as dependent variables. Durations were expressed in milliseconds (ms). Reading Duration was defined as the length of the time interval between stimulus onset on the screen and pressing the pen tip onto the blue trigger zone. Writing Onset Duration was defined as the length of the time interval between pressing the pen tip onto the blue trigger zone and the onset of word writing on paper. Letter 2 Duration and Letter 3 Duration were each defined as the length of the time interval between onset of writing the target letter's first stroke and offset of writing the target letter's last stroke.

For each measure, we report combined analyses for second graders, third graders, and adults to examine whether double-letter processing effects on handwritten word production are modulated by writing proficiency. Reading Duration, Writing Onset Duration, Letter 2 Duration, and Letter 3 Duration were logarithmically transformed; however, back-transformed values are reported throughout the article. For each measure, all data points with residuals exceeding 3 *SDs* from the subjects' and the items' (Reading Duration, Writing Onset Duration) or item pairs' (Letter 2 Duration, Letter 3 Duration) means, respectively, were excluded (Reading Duration: 1.2% of the data; Writing Onset Duration: 1.6%; Letter 2 Duration: 1.0%; Letter 3 Duration: 1.0%).

Analyses were performed using linear mixed-effects models (LMMs; Bates et al., 2015) as implemented in the *lme4* package (Version 1.1-21) in R. The analyses that investigated effects of double-consonant processing on Reading Duration, Writing Onset Duration, Letter 2 Duration, and Letter 3 Duration included Reading Duration, Writing Onset Duration, Letter 2 Duration, or Letter 3 Duration, respectively, as the dependent variable in the LMM, and the effect-coded categorical variables of Consonant Doubling (2 levels: NoCD vs. CD) and Age Group (3 levels: Grade 2 vs. Grade 3 vs. Adults) as fixed effects. Participants and items (Reading Duration, Writing Onset Duration) or item pairs (Letter 2 Duration, Letter 3 Duration) were included as random effects. A full random structure was specified for participants and items or item pairs (Barr et al., 2013). If the model with full random structure did not converge, we trimmed it until it converged. Models were trimmed by first removing correlations between factors, then interactions first for items or item pairs, respectively, then participants, and then by removing one of the slopes. For all measures, only the models with random intercepts converged and are, thus, reported. The significance of the fixed effects was determined with effect

Table 1. Back-transformed estimated Reading Duration (ms) per Consonant Doubling for Grade 2, Grade 3, and Adults.

Consonant Doubling	Grade 2			Grade 3			Adults		
	M (SE)	95% CI	n	M (SE)	95% CI	n	M (SE)	95% CI	n
No	2,301 (131)	[2,050, 2,581]	981	1,607 (91)	[1,434, 1,802]	1,146	597 (48)	[507, 702]	564
Yes	1,981 (113)	[1,766, 2,223]	969	1,417 (80)	[1,265, 1,588]	1,153	577 (46)	[490, 679]	583

M: mean; SE: standard error; CI: confidence interval; n: number of observations.

Table 2. Back-transformed estimated Writing Onset Duration (ms) per Consonant Doubling for Grade 2, Grade 3, and Adults.

Consonant Doubling	Grade 2			Grade 3			Adults		
	M (SE)	95% CI	n	M (SE)	95% CI	n	M (SE)	95% CI	n
No	1,446 (28)	[1,392, 1,503]	964	1,298 (25)	[1,250, 1,348]	1,141	1,092 (30)	[1,034, 1,153]	566
Yes	1,411 (27)	[1,358, 1,466]	965	1,284 (24)	[1,237, 1,334]	1,149	1,100 (30)	[1,042, 1,162]	587

M: mean; SE: standard error; CI: confidence interval; n: number of observations.

coding and type-III Wald tests using the analysis of variance (ANOVA) function provided in the car package (Version 3.0-2; Fox & Weisberg, 2011). Interactions were further decomposed using cell-means coding and post hoc comparisons using the glht function in the multcomp package (Version 1.4-10; Hothorn et al., 2016).

Results

Reading Duration

Our Reading Duration results indicated a significant main effect of Age Group, $\chi^2(2) = 180.75, p < .001$, so that adults were faster than third graders, $\Delta = -925$ ms, $t = -9.84, p < .001$, and second graders, $\Delta = -1,554$ ms, $t = -13.41, p < .001$, and third graders were faster than second graders, $\Delta = -629$ ms, $t = -4.54, p < .001$. More importantly, our results yielded a significant main effect of Consonant Doubling, $\chi^2(1) = 10.86, p = .001$, so that items with double consonants were read faster than items without double consonants, $\Delta = -177$ ms, $t = -3.30, p = .001$. Furthermore, Age Group interacted significantly with Consonant Doubling, $\chi^2(2) = 19.06, p < .001$.

Post hoc analyses were further conducted to investigate Reading Duration differences between the two conditions for each age group (see Table 1). Our results indicated a significant simple main effect of Consonant Doubling for second graders, $\Delta = -320$ ms, $t = -4.41, p < .001$, and third graders, $\Delta = -190$ ms, $t = -3.79, p < .001$, but not for adults, $\Delta = -20$ ms, $t = -0.94, p = .345$. Second and third graders took less time to read items with double consonants than items without double consonants. Effect sizes differed significantly between adults and third graders, $t = 3.49, p < .001$, and between adults and second graders, $t = 4.26, p < .001$, whereas there was no difference between third and second graders, $t = 1.06, p = .290$. In sum, our findings on Reading Duration suggest a facilitatory effect of

Consonant Doubling for second and third graders, but not for adults.

Writing Onset Duration

Our Writing Onset Duration results indicated a significant main effect of Age Group, $\chi^2(2) = 64.58, p < .001$, so that adults were faster than third graders, $\Delta = -195$ ms, $t = -4.96, p < .001$, and second graders, $\Delta = -333$ ms, $t = -8.01, p < .001$, and third graders were faster than second graders, $\Delta = -138$ ms, $t = -3.85, p < .001$. More importantly, Age Group interacted significantly with Consonant Doubling, $\chi^2(2) = 9.11, p = .011$.

Post hoc analyses were further conducted to investigate Writing Onset Duration differences between the two conditions for each age group (see Table 2). Our results indicated a significant simple main effect of Consonant Doubling for second graders, $\Delta = -35$ ms, $t = -2.74, p = .006$, but not for third graders, $\Delta = -14$ ms, $t = -1.25, p = .212$, and adults, $\Delta = 9$ ms, $t = 0.75, p = .456$. Second graders took less time to initiate writing items with double consonants than items without double consonants. Effect sizes differed significantly between adults and second graders, $t = 3.01, p = .003$, whereas there was no difference between adults and third graders, $t = 1.78, p = .076$, and third and second graders, $t = 1.55, p = .120$. In sum, our findings on Writing Onset Duration suggest a facilitatory effect of Consonant Doubling for second graders, but not for third graders or adults.

Letter Duration at Letter Position 2 (vowel preceding consonant cluster)

Our Letter 2 Duration results indicated a significant main effect of Age Group, $\chi^2(2) = 214.63, p < .001$, so that adults were faster than third graders, $\Delta = -481$ ms, $t = -12.44,$

Table 3. Back-transformed estimated Letter Duration (ms) at Letter Position 2 per Consonant Doubling (e.g., “a” in “Kante” and “Kanne,” respectively) for Grade 2, Grade 3, and Adults.

Consonant Doubling	Grade 2			Grade 3			Adults		
	M (SE)	95% CI	n	M (SE)	95% CI	n	M (SE)	95% CI	n
No	913 (51)	[816, 1,022]	988	798 (44)	[713, 892]	1,151	313 (22)	[271, 362]	563
Yes	904 (50)	[807, 1,011]	971	795 (44)	[711, 889]	1,148	317 (22)	[274, 366]	584

M: mean; SE: standard error; CI: confidence interval; n: number of observations.

Table 4. Back-transformed estimated Letter Duration (ms) at Letter Position 3 per Consonant Doubling (e.g., “n” in “Kante” and “Kanne,” respectively) for Grade 2, Grade 3, and Adults.

Consonant Doubling	Grade 2			Grade 3			Adults		
	M (SE)	95% CI	n	M (SE)	95% CI	n	M (SE)	95% CI	n
No	747 (46)	[659, 847]	987	686 (42)	[606, 778]	1,149	258 (20)	[220, 303]	562
Yes	729 (45)	[643, 827]	970	671 (41)	[592, 760]	1,156	270 (21)	[230, 317]	582

M: mean; SE: standard error; CI: confidence interval; n: number of observations.

$p < .001$, and second graders, $\Delta = -593$ ms, $t = -14.16$, $p < .001$, and third graders were faster than second graders, $\Delta = -112$ ms, $t = -2.22$, $p = .027$. Our findings on Letter Duration at Letter Position 2, hence one letter position before the consonant cluster, suggest no effect of Consonant Doubling (see Table 3).

Letter Duration at Letter Position 3 (onset of consonant cluster)

Our Letter 3 Duration results indicated a significant main effect of Age Group, $\chi^2(2) = 173.54$, $p < .001$, so that adults were faster than third graders, $\Delta = -414$ ms, $t = -11.54$, $p < .001$, and second graders, $\Delta = -474$ ms, $t = -12.53$, $p < .001$. More importantly, Age Group interacted significantly with Consonant Doubling, $\chi^2(2) = 18.75$, $p < .001$.

Post hoc analyses were further conducted to investigate Letter 3 Duration differences between the two conditions for each age group (see Table 4). Our results indicated a significant simple main effect of Consonant Doubling for second graders, $\Delta = -18$ ms, $t = -2.24$, $p = .025$, third graders, $\Delta = -16$ ms, $t = -2.36$, $p = .018$, and adults, $\Delta = 12$ ms, $t = 3.19$, $p = .001$. Second and third graders took less time to write the first letter of a double-consonant unit than the first letter of a consonant cluster comprising different consonants. In contrast, adults took more time to write the letter in items with double consonants than items without double consonants. Effect sizes differed significantly between adults and third graders, $t = 3.97$, $p < .001$, and between adults and second graders, $t = 3.89$, $p < .001$, whereas there was no difference between third and second graders, $t = 0.05$, $p = .960$. In sum, our findings on Letter Duration at Letter Position 3, hence at the onset of the consonant cluster, suggest a facilitatory effect of Consonant

Doubling for second and third grades, but an inhibitory effect of Consonant Doubling for adults.

Discussion

We investigated effects of consonant doubling on the kinematics of handwritten word production to gain an insight into the influence of higher levels of cognitive processing onto motor production. Although double letters are common in most alphabetic languages, the available empirical evidence from effects of double-letter processing on handwriting production is limited, while the obtained results are inconsistent across languages (Kandel et al., 2014, 2019; van Galen et al., 1989). Furthermore, even though beginning writers learn early on that certain letters need to be doubled within specific word positions, they have difficulties when spelling words containing double letters (e.g., Treiman & Kessler, 2014). In this study, we asked beginning and skilled writers of German to copy words with double consonants (e.g., “Kanne”) and words without double consonants (e.g., “Kante”) from a computer screen onto a pen tablet, while we recorded handwriting movements with high spatio-temporal resolution. We tested an account put forward by van Galen et al. (1989; see also Caramazza & Miceli, 1990; van Galen, 1990, 1991), which makes predictions about effects of double letters on handwriting at different processing levels, namely the spelling and the motor levels. With regard to the spelling level, the prediction is that writers will yield lower duration values for words containing double letters compared with words that do not contain double letters. With regard to the motor level, the prediction is that writers will be slower writing down a letter that corresponds to the first letter of a double-letter unit (e.g., “n” in “Kanne”) than writing down a letter that corresponds to the

first letter of a consonant cluster (e.g., “n” in “Kante”). We also expected that adults would process double letters as a single letter unit, whereas children in Grade 2 would process double letters as two separate letter units. Based on these predictions, we hypothesised that both facilitatory and inhibitory effects should be observed in adults, yet no effects should be observed in second graders. We reasoned that Grade 3 is the point in time when children’s writing behaviour becomes adult-like, so double-letter processing in these two groups should be similar.

Our results revealed that second graders take less time to initiate writing words with double consonants than words without double consonants, while both second and third graders take less time to read words with double consonants compared with words without double consonants. Moreover, second and third graders write down a letter faster when it corresponds to the first letter of a double-letter unit than to the first letter of a consonant cluster. In contrast, skilled writers write down a letter slower when it corresponds to the first letter of a double-letter unit than when it corresponds to the first letter of a consonant cluster. These findings show thus a facilitatory effect of Consonant Doubling on early and late measures of handwriting production in beginning writers, and an inhibitory effect of Consonant Doubling on a late measure of handwriting production in skilled writers. In sum, effects of Consonant Doubling on handwriting production were similar in second and third graders, but differed between children and adults. Critically, the facilitatory effects observed in children are consistent with the account put forward by van Galen et al. (1989; see also Caramazza & Miceli, 1990; van Galen, 1990, 1991), which postulates that similarity of adjacent linguistic units reduces short-term memory demands at the spelling level. The inhibitory effects observed in adults are also consistent with van Galen et al.’s (1989) account, which posits that similarity of strokes in the motor buffer slows down the production of similar letters at the motor level.

Before we discuss our findings, it is worth highlighting the difference between a direct copy task, which has been used in previous kinematic studies on double-letter processing (Kandel et al., 2014, 2019; van Galen et al., 1989), and the delayed copy task used in this study. The main difference between the two tasks is that the delayed copy task that we used required that writers visualise mentally the to-be-written stimulus prior to writing onset. Thus, it mimicked written object naming and spelling to dictation, rather than copying, where the stimulus word remains visible throughout the writing process. However, input processing obviously differs between the different writing tasks due to the different nature of the stimulus (auditory vs. visual). More importantly, specific features of the delayed copy task could potentially affect children’s and adults’ writing behaviour differently. For example, even though we did not observe excessively long reading durations, it is likely that our participants, especially beginning

writers who are also beginning readers, read the item twice before they began writing, or perhaps they checked its spelling in detail. Therefore, we do acknowledge that the observed differences between beginning and skilled writers might be due to the read-retain-write process that was enforced by our experimental paradigm. Further research would be required to determine how differences between different age groups reflect more general processes that occur when children and adults write in other contexts.

Another issue associated with the delayed copy task relates to the time that writers have between stimulus presentation on the screen and writing onset on the paper (“classical Latency”). This time span is typically associated with preparation of the first stroke of the item’s first letter, as well as upstream processes (e.g., Kandel & Perret, 2015; Lambert et al., 2008; Roux et al., 2013). We added a quick pen-tip-press movement to this time span, as a result of which the stimulus disappeared from the screen. We then divided classical Latency into “Reading Duration” and “Writing Onset Duration.” However, given that no time limit was set for the pen-tip press, Reading Duration and Writing Onset Duration had no fixed end point or starting point, respectively. As a result, different participants may have decided to press the pen tip at different processing stages, and so our results should be interpreted with caution. It is worth pointing out, however, that our participants were instructed to read the stimulus word before they started writing, and we are confident that they pressed the pen tip as soon as they finished reading it, because delaying this process would require higher short-term memory demands, thus increasing significantly the task’s difficulty, as well as its duration.

Importantly, Lambert et al. (2008) have previously used the present paradigm and similar measures to dissociate effects of visual encoding (“Visual Encoding Time”) and writing preparation prior to writing onset (“Latency 1”). Critically, they also carried out an experiment that used a direct copy task, in which the stimulus disappeared at writing onset without a pen-tip press, and measured classical Latency. Crucially, they observed an identical pattern of results with regard to the factors of interest in terms of the two latency measures. Therefore, there is reason to believe that Writing Onset Duration reflects central orthographic processes, just like the classical Latency measure does. More generally, Lambert et al.’s (2008) study demonstrates that handwriting production is very similar in the direct and the delayed copy task.

How can we explain the observed differences between children and adults? In children, we obtained facilitatory effects of Consonant Doubling on Reading Duration. In our task, Reading Duration reflects the amount of processes that are necessary to recognise the letter string and maintain it in short-term memory, with the specific purpose of reproducing its spelling. Items with double letters involve a letter that is orthographically redundant, in the sense that the number of different letters that need to be recognised is

fewer (e.g., “Kanne” has four different letters, whereas “Kante” has five different letters). Thus, it is likely that lower short-term memory demands for words with double letters sped up spelling-to-sound conversion, thus decreasing Reading Duration. Furthermore, phonological representations of items with double letters are shorter (e.g., “Kanne” → /kanə/) than those of items without double letters (e.g., “Kante” → /kantə/), which reduces processing demands at the phonological buffer. This could also explain the facilitatory effects observed in children prior to the pen-tip press. The reason why such facilitatory effects were not observed in adults could be due to the lower impact of the above two factors on adult handwriting production, given that skilled readers tend to focus on larger orthographic units (i.e., words), especially when these are highly frequent, as it was the case in our study (see also Ziegler & Goswami, 2005).

In second graders, we obtained facilitatory effects of Consonant Doubling on Writing Onset Duration. This measure reflects central and peripheral orthographic processes (spelling and motor level) that are required for writing down the first stroke of the item’s first letter. The lower number of phonemes in words with double letters likely facilitates phoneme segmentation during phonology-to-orthography conversion. This is because words with double letters comprise a single consonant, whereas words without double letters comprise a consonant cluster at the position that corresponds to the double-letter unit or cluster of consonant letters, respectively (e.g., /n/ surrounded by /anə/ in “Kanne,” but by /antə/ in “Kante”). As a result, mapping in words with double letters (e.g., /n/ onto <nn>) would speed up the output for one or both of these letters relative to words without double letters (e.g., /n/ onto <n>). This could explain the facilitatory effects observed between pen-tip press and writing onset in our second graders. The reason why such facilitatory effects were not observed in third graders and in our adult sample could be due to the fact that central orthographic processes are more automatized in skilled writers. Indeed, central orthographic processing might already start during the pen-tip-press movement in more skilled writers, because they have the capacity to do this in parallel to motor execution (e.g., Kandel & Perret, 2015; Roux et al., 2013). As such, effects of double-letter processing would be more likely reflected on Reading Duration, rather than on Writing Onset Duration.

Letter Duration is a measure that reflects the processes that are required to retrieve information from the orthographic buffer (spelling level) and to program motor execution (motor level). It also reflects necessary upstream processes (e.g., van Galen et al., 1989). As far as adults are concerned, we observed inhibitory effects of Consonant Doubling on the onset of double-letter units. According to van Galen et al. (1989), such inhibitory effects, which are manifested as movement delays at the onsets of double-letter units, are due to difficulty in retrieving similar strokes from the motor buffer. These results are consistent

with those obtained in Dutch (van Galen et al., 1989) and French (Kandel et al., 2014). In contrast to skilled writers, children do not have a similar difficulty, because it is generally believed that they operate on a letter-by-letter basis (e.g., Landerl & Thaler, 2013; Weingarten, 1998). Hence, they are thought to retrieve from the motor buffer strokes of single letters, rather than strokes of a double code. Accordingly, we observed facilitatory effects of Consonant Doubling on the onset of double-letter units in both second and third graders.

It is worth noting that van Galen et al.’s (1989) account predicts that writers should be faster writing down the same letter (e.g., “a” in “Kanne” and “Kante”) when it precedes a double-letter unit than when it precedes a consonant cluster, because short-term memory demands at the spelling level are lower in the former compared with the latter type of words. However, neither the present study nor other study on double-letter processing (Kandel et al., 2014, 2019) yielded effects of Consonant Doubling on handwriting production at this letter position. Given that van Galen et al.’s (1989) account is based on empirical evidence from Dutch, whereas the empirical evidence from all other studies comes from English, French, German, and Italian, it could well be that the presence/absence of such effects is language specific. Thus, cross-linguistic research would be needed to explain the inconsistency of these findings.

Although third graders yielded relatively low Reading Duration, Writing Onset Duration, and Letter Duration at Letter Position 2, as well as substantially fewer errors (12.9%) than second graders (24.1%), thus showing more adult-like writing characteristics, in contrast to our predictions, their writing behaviour still differed from the writing behaviour of adults. In particular, third graders (as well as second graders) yielded effects of Consonant Doubling on measures that are thought to reflect demands of cognitive processes in reading and spelling (i.e., Reading Duration and Letter Duration at Letter Position 3). For example, Letter Duration at Letter Position 3 was similar between Grade 2 and 3, suggesting that the onset of consonant clusters is special for this age group. Further research is needed to determine the time point in writing development, at which reading and spelling processes are not modulated by the characteristics of consonant clusters, at least with regard to the experimental paradigm used in this study. Real-time data are critical for achieving this.

In conclusion, our study used a set of tightly controlled experimental stimuli to investigate effects of consonant doubling on handwriting production in the German language. Our work contributes to the empirical evidence in handwriting research showing that double letters are functional units in skilled but not developmental handwriting. Further developmental research with children from different grades and/or languages is needed to track the point in time at which double letters are processed during development. Another challenge in future research is to determine

whether findings from kinematic studies on double-letter processing using copy tasks generalise to more ecologically valid writing tasks.

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Supplementary material

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Note

1. Slashes and angle brackets indicate phonological and orthographic representations, respectively; dots indicate syllabic boundaries.

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