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Syllabic processing in handwritten word production in German children and adults

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Abstract:
Syllables are thought to be processing units in handwritten word production. Yet, little is known about whether the orthographic characteristics of different languages influence syllabic processing during handwriting, which is critical for the evaluation and further development of extant models of handwritten language production. In the present study, we manipulated syllabic ambiguity, a characteristic of the German language, to investigate the role of syllables in handwritten word production in German. Forty-four 10 to 12-year-old children and fourteen adults were asked to write on pen tablets five-letter disyllabic words that varied in terms of their syllabic ambiguity, while their handwriting was recorded with high spatiotemporal resolution. Productions were analyzed in terms of Mean Stroke Duration (MSD) and Writing Onset Duration (WOD). Increased MSD at syllable boundaries was observed across conditions for both children and adults. There was no difference in WOD across conditions. Our findings offer support for the idea that syllables are functional units in handwriting production in German and motivate the further development of the spelling module in models of handwritten language production.

1. Introduction

There is evidence from a number of languages that writers make use of sublexical units such as syllables during the handwritten production of multisyllabic words. This has been found in Romance languages such as Spanish (e.g., Álvarez, Cottrell, & Afonso, 2009), Catalan (e.g., Soler Vilageliu & Kandel, 2012), and French (e.g., Kandel, Álvarez, & Vallée, 2006), but also in a Germanic language such as Dutch (Bogaerts, Meulenbroek, & Thomassen, 1996). Similar research in German has yielded inconsistent results (e.g., Nottbusch, 2008; Weingarten, 1998). For example, Weingarten (1998) failed to find syllabic effects on handwritten word production for children under 13 years but observed such effects in young adults. In contrast, Nottbusch (2008) found syllabic effects on handwritten word production in 11- to 13-year-old children. Further, there has been some inconsistency in the literature with regards to the nature of syllabic processing effects across different languages. Results from studies in French, for example, suggest that syllabic processing becomes orthographic in nature by the age of 8 (Kandel, Hérault, Grosjacques, Lambert, & Fayol, 2009), while results from studies in German indicate that children between 11 and 13 years process syllables phonologically (Nottbusch, 2008). Determining the role and nature of syllabic processing across different languages is critical for the further development of models of handwritten language production (e.g., Kandel, Peereman, Grosjacques, & Fayol, 2011; van Galen, 1991).

How can we investigate syllabic processing in handwriting production? Experimental research in this domain is typically based on recordings of handwriting with high spatiotemporal resolution. Results show that skilled writers change movement duration in the course of word production systematically. In particular, increases in movement duration have been observed at syllable boundaries or

syllable onsets (e.g., Álvarez et al., 2009; Bogaerts et al., 1996; Kandel et al., 2006; Weingarten, 1998). A number of other psycholinguistic variables (e.g., lexical status, orthographic regularity, graphemic complexity, letter quantity) produce increases in movement duration too. For example, pseudowords produce longer movement durations than words (Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013), irregular words yield longer movement durations than regular words (Roux et al., 2013), longer graphemes produce longer movement durations (Kandel & Spinelli, 2010), and double letters yield longer movement durations than single letters (Kandel, Peereman, & Ghimenton, 2014; but see Kandel, Peereman, & Ghimenton, 2013; Kandel, Peereman, Ghimenton, & Perret, 2017, for an opposite effect). These results indicate that whenever a conflict is induced due to linguistic ambiguity, movement durations increase too. Critically, such increases in movement duration suggest that the nature of the relationship between central (cognitive) and peripheral (motor) writing processes is not staged, but instead cascaded. In other words, higher-level cognitive processes are not completed before motor production, but cascade all the way down to influence handwriting (e.g., Kandel et al., 2013; Roux et al., 2013).

Studies on developmental handwriting production have often shown that syllables are used as programming units. This is the case for French children aged between 6 and 7 years (Kandel & Soler, 2010; Kandel, Soler, Valdois, & Gros, 2006; Kandel & Valdois, 2006a, 2006b), 7 and 8 years (Kandel & Valdois, 2006a, 2006b), 8 and 10 years (Kandel et al., 2011; Kandel & Valdois, 2006b), as well as 10 and 11 years (Kandel & Valdois, 2006b). However, in other languages, the evidence on the role of syllables varies. For example, in shallow orthographies, such as Spanish, words, rather than syllables, are thought to be functional units of handwriting in 6 to 8-yearold children (Kandel & Valdois, 2006a). In contrast, bilingual French and Spanish children aged between 6 and 8 years mostly revealed a syllabic programming strategy when writing both in French and Spanish (Kandel & Valdois, 2006a). In particular, children programmed the corresponding gestures for the production of the first syllable of multisyllabic words before writing onset. Similarly, in Catalan, a language with a shallower orthography than French but a deeper orthography than Spanish (Kandel & Soler, 2010), children aged between 5 and 7 years were found to program handwritten word production syllabically (Kandel & Soler, 2010; Soler Vilageliu & Kandel, 2012). In sum, findings from French and Catalan indicate that beginning writers break words into smaller linguistic units such as syllables (Kandel et al., 2009; Kandel et al., 2011; Kandel & Soler, 2010; Kandel, Soler et al., 2006; Kandel & Valdois, 2006a; Kandel & Valdois, 2006b; Soler, Vilageliu, & Kandel, 2012). However, this is not the case in Spanish, where beginning writers tend to use word-sized units (Kandel & Valdois, 2006a).

With regards to the German language, the available empirical evidence on syllabic processing in handwriting production is limited and rather inconsistent. For example, Weingarten (1998) failed to find syllabic effects on handwritten word production in second, fourth, and seventh graders, who typically range between 7 and 8, 9 and 10, and 12 and 13 years, respectively, but observed such effects in young adults. Weingarten (1998) suggested that developing writers rely on graphemes and start using syllables only when they become skilled writers. In contrast, Nottbusch (2008) observed syllabic effects on handwritten word production in 11 to 13-year-old children. The discrepancy between the results obtained by Nottbusch (2008) and Weingarten (1998) could be due to differences in the experimental materials that were used in the two studies. Critically, items of different syllabic and morphological structure were used in the two studies and both of these variables are thought to influence handwriting processes (e.g., Kandel et al., 2006; Kandel, Spinelli, Tremblay, Guerassimovitch, & Álvarez, 2012). In particular, in the Nottbusch (2008) study, the vast majority (83%) of the multisyllabic items were disyllabic, whereas disyllabic items in the Weingarten (1998) study only comprised 25% (grade 2), 42% (grade 4), or 39% (grade 7) of the multisyllabic items. This is an important difference, insofar as the prevalence of disyllabic items may have induced certain syllabification strategies. Further, only in the Weingarten (1998) study, a significant number of compound words were used in the experiments that were carried out with children. Morphological processing is thought to occur earlier in time than syllabic processing (Kandel, 2009). As such, syllabic effects on handwriting in the Weingarten (1998) study may have been masked by the influence of other critical psycholinguistic variables on handwriting production.

As far as studies on the nature of syllable units are concerned, the empirical evidence is rather limited. Kandel et al. (2009) asked 8- to 10-year-old children to write words, which were orthographically always disyllabic, but phonologically either di- or monosyllabic (e.g., <BAL.CON> [1], /bal.kõ/, and <BAR.QUE>, /baRk/, respectively). In the former condition, the onset of the second orthographic and phonological syllable coincided and yielded increases in movement duration. In the latter condition, the authors observed increases in movement duration at the onset of the second orthographic syllable. Kandel et al. (2009) concluded that syllables are processed orthographically rather than phonologically by 8-year-old French children. Similar research on syllabic processing in German (Nottbusch, 2008; Weingarten, 1998) indicates, however, a role of phonology during handwritten word production both in developing and skilled writers.

The observed effects in the literature may be explained by van Galen's (1991) model of handwritten language production. According to this model, the production of handwritten language comprises three processing levels prior to real-time trajectory formation: (1) a conceptual level, which consists of modules for the activation of intentions, semantic retrieval, and syntactic construction; (2) a spelling level; and (3) a motor level, which consists of modules for the selection of allographs, size control, and muscular adjustment. These modules exhibit a hierarchical structure, so that the output from each module forms the input to the next module. 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. An assumption of the model is that different types of linguistic units are processed within each module, with larger units (i.e., ideas, concepts, and phrases) processed at the highest level, medium-sized units (i.e., words) processed at the intermediate level, and

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[1] Angle brackets and slashes indicate orthographic and phonological representations, respectively; a dot indicates a syllable boundary.

smaller units (i.e., graphemes, allographs, and strokes) processed at the lowest level. The original formulation of van Galen's (1991) model does not assume the processing of syllables at the spelling level. Also, in contrast to the conceptual and the motor levels, the spelling level is underspecified in this model.

However, other models in this research domain have offered an account of how the spelling module might operate, and what grain sizes the linguistic units in such module might be. With regards to the spelling module, a dual-route theory has been put forward, according to which writers generate first an orthographic representation of the word to-be-spelled (e.g., Bonin, Méot, Lagarrigue, & Roux, 2015; Miceli & Costa, 2014). Orthographic representations are abstract graphemic descriptions of letter sequences, which encode information about letter position, letter identity (spanning grain sizes from single to n-graphs with n > 1, hence simple or complex graphemes, respectively), letter type (i.e., consonants, vowels), syllabic structure (i.e., onset, nucleus, coda), and letter quantity (Rapp & Fischer-Baum, 2014; see also, e.g., Kandel et al., 2011). Orthographic representations are then thought to be processed by an orthographic working memory component, which maintains information active and ensures that letters are produced in a correct serial order (e.g., Miceli & Costa, 2014; Rapp, Purcell, Hillis, Capasso, & Miceli, 2016). According to dual-route theory, orthographic representations 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 (e.g., Bonin et al., 2015; Miceli & Costa, 2014). Both routes are thought to be active in parallel and to interact during the determination of the final spelling (e.g., Houghton & Zorzi, 2003; Roux et al., 2013). With regard to the grain sizes of the linguistic units in the spelling module, the lexical route is assumed to activate whole-word orthographic representations of the words to-be-spelled, whereas the sublexical route is thought to activate sublexical units that might correspond to syllables or phonemes (Miceli & Costa, 2014).

A revised version of van Galen's (1991) conception of the spelling module (Kandel et al., 2011) posits that skilled writers activate word-sized orthographic representations, which in turn activate syllables and then graphemes prior to the activation of the motor level. The first syllable is assumed to be retrieved before writing onset, while subsequent syllables are activated online. Following van Galen's (1991) idea of parallel processing, Kandel et al.'s (2011) model predicts that activation of the corresponding syllabic unit in parallel to real-time trajectory formation increases processing load and, accordingly, delays movement execution at syllable boundaries (see also Kandel et al., 2006). Although Kandel et al. (2011) mention a potential role of phonology during grapheme processing, the relationship between phonology and orthography remains underspecified in the model. Given the previous findings on handwriting production in German (e.g., Nottbusch, 2008; Weingarten, 1998), it appears to be likely that syllabic units may be activated in the spelling module by means of the sublexical route, and further processed by motor modules prior to the selection of orthographic word units. Considering both the lexical and the sublexical route in the spelling module seems, thus, to be critical for explaining the effects observed across different languages. In the present study, we manipulated syllabic ambiguity, a characteristic of the German language, to investigate syllabic processing in handwritten word production in German children and adults.

Most German words are multisyllabic and have a trochaic syllable structure, that is, a sequence of stressed (full) and unstressed (reduced) syllables (e.g., Eisenberg, 2013). German words may vary in terms of their syllabic ambiguity. For example, words like KUNDE ("customer"), which involve two intervocalic consonants, are syllabically unambiguous (Wiese, 2000). This is because in these words, only a single syllabification is possible (i.e., /CVC.CV/[2]). However, words like KUGEL ("bowl"), which involve a single intervocalic consonant, contain certain syllabic ambiguity (Wiese, 2000). This is because in these words, two different syllabifications are possible (i.e., /CV.CVC/ or /CVĊVC/), so that the middle consonant is either onset of the reduced syllable or ambisyllabic. Another interesting aspect of the German language is the use of silent letters to particularly denote vowel lengthening in written words. This occurs in the case of two consecutive vowel letters, that is, <IE, AA, EE, OO>, or a vowel followed by the consonant <H>. In these letter sequences, the second letter is always silent and functions as a "lengthening marker" (Noack, 2002, p. 150) in reading. Linguistic research on the German writing system indicates that these letter sequences do not form complex graphemes, but comprise two simple graphemes (e.g., Eisenberg, 2013; Noack, 2002). Thus, words like KUHLE ("hollow") are highly ambiguous from a writing perspective because they contain a silent letter at the syllable boundary that writers need to take into account during writing. Further, there is a mismatch between the phonological and orthographic representations of such words (i.e., /CV.CV/ and <CVX.CV>[3], respectively), thus causing additional difficulties at the syllable boundary. In particular, the phonological onset of the second syllable occurs at the third position, that is, where the silent letter is encountered in the KUHLE words, while the orthographic onset of the second syllable occurs at the fourth position. Hence, German words such as KUNDE and KUGEL can be used to investigate syllabic effects on handwriting production in words, which involve canonical syllable structures that are frequently used in handwriting research (e.g., Kandel et al., 2006), but differ in the amount of ambiguity at the syllable boundary. Further, words such as KUHLE, which contain a mismatch between phonology and orthography, can be used to shed further light onto the nature of syllabic processing in German handwritten word production.

In the present study, we investigated effects of syllabic processing on handwritten word production in 10- to 12-year-old German children and adults. Children in this age group were chosen, because according to previous findings (e.g., Kandel & Perret, 2015a, 2015b), age 9 to 10 appears to be the point in time when motor programming during handwriting becomes stable, with no significant changes in motor behavior observed until adolescence. Hence, the children and adult groups in our study were not expected to differ in terms of their motor behavior during handwriting, whereas on the basis of previous findings in the German language (Weingarten, 1998), differences between the two groups in spelling behavior would indicate reliance on different linguistic units as a function of writing proficiency. It is also worth noting that on the basis of the results from a developmental study carried out in French (Kandel &

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[2] C and V denote a consonant and a vowel, respectively.

[3] X denotes a silent consonant or vowel in orthographic representations.

Valdois, 2006b), we expected no differences in terms of syllabic processing effects on handwriting across children of different ages in our sample.

Participants were asked to write disyllabic five-letter words, which varied in the degree of syllabic ambiguity, on pen tablets while we recorded their handwritten productions with high spatiotemporal resolution. We reasoned that syllabic ambiguity will create a conflict at the syllable boundary, and, as a result of this conflict, the corresponding duration of the letter at the critical position will increase (Kandel & Perret, 2015b; Roux et al., 2013). In particular, we hypothesized that syllabically unambiguous words like KUNDE would exhibit syllabic effects on handwriting, so that increases in movement duration would be observed from the third to the fourth letter, hence at the onset of the second syllable (i.e., /d/). For words with low syllabic ambiguity like KUGEL, we hypothesized that increases in movement duration would likely occur from the second to the third letter, hence on the middle consonant (i.e., /g/). In words with high syllabic ambiguity, such as KUHLE, the phonological onset of the second syllable (i.e., /l/) occurs at the third letter, which is where the silent letter is encountered (i.e., <H>), thus creating a conflict between phonology and orthography. Following the literature on cascaded processing in handwriting production (e.g., Kandel & Perret, 2015b; Roux et al., 2013), we hypothesized that for these words, increases in movement duration would occur from the second to the third letter, hence on the silent letter, which is the phonological onset of the second syllable, rather than at the letter L, which is the orthographic onset of the second syllable. On the assumption that young writers process printed words phonologically, so that sublexical processing is at play, and adults process them orthographically, so that lexical processing is at play, syllabic ambiguity effects could be more prominent in children than in adults. However, it is also likely that phonological processing persists in adults (Roux et al., 2013; Weingarten, 1998).

To test the hypothesis that syllabic ambiguity creates a conflict that must be resolved either before or during motor production, it is also worth taking into account a measure that is associated with spelling preparation, namely the time taken between stimulus presentation and writing onset. This measure is known as Writing Onset Duration (WOD; see Kandel & Perret, 2015b; Roux et al., 2013). If syllabic ambiguity does not influence WOD, then the Low and High syllabic ambiguity condition (KUGEL and KUHLE items, respectively) should yield lower values than the No syllabic ambiguity condition (KUNDE items). This is because the items in the former conditions have shorter first syllables, in terms of number of sounds, than the items in the latter condition. Alternatively, if syllabic ambiguity influences WOD, then we should observe the opposite, that is, the Low and High syllabic ambiguity condition should yield higher values than the No syllabic ambiguity condition.

2. Method

2.1. Participants

Fifty-five children from the Berlin area participated in the experiment. A small gift was given to them as compensation for their participation. A group of 15 adults also participated in the experiment for monetary reimbursement. For the present analysis, only participants providing full data were included. This process resulted in the exclusion of nine children and one adult due to a technical recording error caused by the recording software, which produced empty data files. In addition, only participants writing the whole word in uppercase letters were included, resulting in the exclusion of two additional children. Forty-four children (38 right-handed, 6 left-handed; 27 females), who were 11.4 years old on average (SD = 0.8 years, $Range$ = [10–12] in years) and 14 adults (10 righthanded, 1 left-handed, 3 ambidextrous; 7 females), who were 24.3 years old on average (SD = 3.4 years, $Range$ = [19–32] in years), were thus included in the analysis. All participants reported to have learned German before the age of 6.

The study was approved by the ethics committee of the Max Planck Institute for Human Development, Berlin, Germany. Adults gave written informed consent in accordance with the Declaration of Helsinki. Children gave oral consent, while written consent was obtained from their parents.

2.2. Materials

Thirty German disyllabic five-letter nouns were selected as targets (see Appendix). The items were assigned to three conditions that manipulated syllabic ambiguity: No syllabic ambiguity condition (e.g., KUNDE), Low syllabic ambiguity condition (e.g., KUGEL), and High syllabic ambiguity condition (e.g., KUHLE).

Each of the ten word triplets that were used in the study, such as KUNDE, KUGEL, and KUHLE, shared their initial CV sequence. All conditions were matched on normalized type frequency ($F(2, 18)$ = 1.41, p = .270) and Orthographic Levenshtein Distance 20 (OLD20; Yarkoni, Balota, & Yap, 2008; $F(2, 18)$ = 0.16, p = .855), as well as on summed bigram type frequency ($F(2, 18)$ = 1.64, p = .221) and position-specific bigram type frequency at the orthographic syllable boundary ($F(2, 18)$ = 1.27, p = .305), according to the childLex norms (Version 0.16.03; Schroeder, Würzner, Heister, Geyken, & Kliegl, 2015).

2.3. Procedure

Participants were tested individually in a quiet room. Each target word was presented in black 24-point uppercase Arial font on white background in the center of a 19-inch monitor screen. An auditory signal and a blank screen preceded each trial for 1500 ms. The stimulus remained on the screen until participants wrote down their response. Participants were given a Wacom Intuos4 Inking Pen and were asked to copy the word using uppercase letters and without making any errors (as per Kandel et al., 2006, and Kandel et al., 2011, no explicit instruction on pen lifts was given). In Berlin, children in grade 1 learn first how to write printed script, hence printed lower- and uppercase letters. As soon as they have completed motor acquisition and have acquired basic literacy skills, they

are additionally introduced to cursive script. Thus, uppercase letter handwriting was familiar to our participants. Responses were made on a ruled sheet of paper (horizontal length of a line 60 mm each trial; vertical distance between lines 12 mm) adjusted to a Wacom Intuos4 L Tablet that was connected to an IBM-compatible laptop running Windows XP. Pen-tip position and pen-tip pressure were registered in real-time (sampling rate 200 Hz; spatial resolution 200 lpmm) controlled by Ecriture from the Ductus software package (Version 1.01.218; Guinet & Kandel, 2010). After each trial, the experimenter initiated the next trial. Three practice trials preceded the experimental trials.

2.4. Analysis

For the analysis of the handwritten productions, each word was manually segmented into its individual letters and strokes. Ductus was used for the segmentation based on the raw data files that were recorded by Ecriture. A letter start was defined by a pen-tip pressure value $P > 0$, while a letter end was defined by a pen-tip pressure value $P = 0$, which refers to criteria commonly used for uppercase letter segmentation in handwriting research (e.g., Kandel et al., 2006). With regards to stroke segmentation, there is no standard definition for uppercase letters (Kandel & Spinelli, 2010). Thus, we combined different criteria commonly used for stroke segmentation in handwriting research (e.g., Meulenbroek & van Galen, 1990). We segmented each letter produced by each participant separately: A stroke started after each pen lift, that is, at each first point with a pen-tip pressure value $P > 0$ and preceding points with a pen-tip pressure value $P = 0$. Hence, a stroke started either at the letter onset or after a pen lift within a letter. Additionally, a stroke started at points with a minimum in absolute velocity and, at the same time, a maximum in curvature, as long as the pen-tip was on the paper ($P > 0$). Incorrect responses and misspellings were treated as errors and discarded. This process resulted in the exclusion of 12.4% of the data for children and 3.1% of the data for adults.

Mean Stroke Duration (MSD) and Writing Onset Duration (WOD) were calculated and used as dependent variables. MSD was defined as a ratio of total writing duration for a single letter to number of strokes needed per letter (e.g., Bogaerts et al., 1996; Kandel & Spinelli, 2010). WOD was defined as the length of the time interval between stimulus onset and word writing onset (e.g., Kandel & Perret, 2015b; Roux et al., 2013). Both measures were expressed in milliseconds (ms).

We report separate analyses for children and adults for each measure. However, we also combined the children and adult MSD data in a single analysis to examine whether syllabic processing effects on handwritten word production are modulated by writing proficiency. MSD and WOD were logarithmically transformed; however, back-transformed values are reported throughout the article. Outliers were trimmed for children and adults separately. All data points with residuals exceeding 2.5 standard deviations from the subjects' and the items' means were excluded (MSD children: 1.6%, adults: 1.5%; WOD children: 1.5%, adults: 2.5%). Analyses were performed using linear mixed-effects models (Bates, Mächler, Bolker, & Walker, 2015) as implemented in the lme4 package (Version 1.1-12) in R. The significance of the fixed effects was determined with effect coding and type-III Wald tests using the Anova function provided in the car package (Fox & Weisberg, 2011). Interactions were further analyzed using cell-means coding and post-hoc comparisons using the glht function in the multcomp package (Hothorn et al., 2016).

3. Results

3.1. Mean Stroke Duration

The analysis that investigated effects of syllabic processing on MSD included MSD as the dependent variable in the linear mixed-effects model (LMM) and the effect-coded categorical variables of Letter Position (5 levels: 1 vs. 2 vs. 3 vs. 4 vs. 5) and Syllabic Ambiguity (3 levels: No vs. Low vs. High) as fixed effects. To control for bigram frequency and for letter complexity at each letter position, the Position-Specific Bigram Type Frequency (10–1784 occurrences per million) and the Total Trajectory Length produced per letter (children: 0.30–10.37 cm; adults: 0.25–4.67 cm) were included in the model as standardized continuous fixed effects. Intercepts for subjects and items were included as random effects.

Our results indicated a significant main effect of Total Trajectory Length per letter, so that MSD increased with increasing Total Trajectory Length for children, $\chi^2(1) = 402.48$, $p < .001$, and adults, $\chi^2(1) = 81.64$, $p < .001$. The main effect of Letter Position was also significant for both children, $\chi^2(4) = 265.25$, $p < .001$, and adults, $\chi^2(4) = 143.80$, $p < .001$. More importantly, Letter Position interacted significantly with Syllabic Ambiguity for children, $\chi^2(8) = 147.76$, $p < .001$, and adults, $\chi^2(8) = 44.37$, $p < .001$.

Post hoc analyses were further conducted to investigate MSD differences across letter positions (see Table 1). In the No syllabic ambiguity condition, MSD increased significantly from the third to the fourth letter (children: $\Delta = 33$ ms, $t = 7.68$, $p < .001$; adults: $\Delta = 23$ ms, $t = 5.11$, $p < .001$), hence at the syllable boundary (i.e., D in KUNDE), but decreased significantly from the fourth to the fifth letter in children ($\Delta = -16$ ms, $t = -2.69$, $p = .007$), hence from the onset to the nucleus of the second syllable (i.e., E in KUNDE), but not in adults ($\Delta = 0$ ms, $t = -0.01$, $p = .993$). In the Low syllabic ambiguity condition, MSD increased significantly from the second to the third letter (children: $\Delta = 53$ ms, $t = 13.01$, $p < .001$; adults: $\Delta = 34$ ms, $t = 8.13$, $p < .001$), hence from the vowel of the first syllable to the middle consonant (i.e., G in KUGEL), but decreased significantly from the third to the fourth letter in children ($\Delta = -24$ ms, $t = -5.32$, $p < .001$), hence from the onset to the nucleus of the second syllable (i.e., E in KUGEL), but not in adults ($\Delta = -6$ ms, $t = -1.25$, $p = .211$). In the High syllabic ambiguity condition, MSD increased significantly from the second to the third letter (children: $\Delta = 24$ ms, $t = 6.25$, $p < .001$; adults: $\Delta = 17$ ms, $t = 4.03$, $p < .001$), hence from the vowel of the first syllable to the silent letter (i.e., H in KUHLE), but remained similar from the third to the fourth letter (children: $\Delta = -7$ ms, $t = -1.66$, $p = .097$; adults: $\Delta = 3$ ms, $t = 0.60$, $p = .550$), hence from the silent letter to the onset of the second syllable (i.e., L in KUHLE). In those cases of the aforementioned comparisons where there was a significant difference, it also remained after Bonferroni

Table 1
Back-Transformed Estimated Mean Stroke Duration (ms) per Letter Position and Syllabic Ambiguity for Children and Adults.

DV: MSD	Syllabic Ambiguity		Letter Position				
			1	2	3	4	5
Children	No	< CVC.CV >	245	211	221	254	237
	Low	< CV.CVC >	241	210	264	239	226
	High	< CVX.CV >	243	210	234	227	238
Adults	No	< CVC.CV >	178	154	159	182	182
	Low	< CV.CVC >	182	155	189	183	174
	High	< CVX.CV >	178	153	170	173	185

Note. Dependent variable (DV). Consonant (C), vowel (V), silent consonant or vowel (X).

correction. Our findings indicate increases in cognitive load at syllable boundaries, even after controlling for bigram frequency and letter complexity, which is thought to influence handwriting production (e.g., Kandel et al., 2011; van Galen, Meulenbroek, & Hylkema, 1986). Further, our results in the High syllabic ambiguity condition suggest that the nature of syllabic processing is phonological, because movement duration increased at the silent letter, hence at the position where a conflict between phonological and orthographic representations occurs. We believe that the adults showed no decrease in MSD from the fourth to the fifth letter in the No syllabic ambiguity condition and from the third to the fourth letter in the Low syllabic ambiguity condition due to the complexity of the letter E in terms of motor programming (van Galen et al., 1986), which occurred in most stimuli in these particular positions. We take up this issue in the Discussion section.

Further, we sought to determine whether children and adults differed in terms of their writing behavior, by combining them in a single analysis that included Age Group (2 levels: children vs. adults) as an effect-coded categorical fixed effect in the LMM. All data points with residuals exceeding 2.5 standard deviations from the subjects' and the items' means were excluded (i.e., 1.5% of the data points). The results from this analysis showed that MSD was significantly longer in children than in adults, $\chi^2(1) = 28.34$, $p < .001$, yet no significant interactions with Age Group were observed (Age Group by Letter Position: $\chi^2(4) = 2.74$, $p = .602$; Age Group by Syllabic Ambiguity: $\chi^2(2) = 3.51$, $p = .173$; Age Group by Letter Position by Syllabic Ambiguity: $\chi^2(8) = 2.75$, $p = .949$).

In addition, we examined whether developmental differences occurred within the children group by including Age (10–12) as a standardized continuous fixed effect in the LMM of the child data. The results from this analysis showed that neither the main effect of Age, $\chi^2(1) = 1.34$, $p = .247$, nor any of the interactions with Age were significant (Age by Letter Position: $\chi^2(4) = 7.96$, $p = .093$; Age by Syllabic Ambiguity: $\chi^2(2) = 3.21$, $p = .201$; Age by Letter Position by Syllabic Ambiguity: $\chi^2(8) = 6.78$, $p = .561$). In sum, our results indicate syllabic processing effects on handwritten word production in both children and adults.

3.2. Writing Onset Duration

The analysis that investigated effects of syllabic processing on WOD included WOD as the dependent variable in the linear mixed-effects model (LMM) and the effect-coded categorical variable of Syllabic Ambiguity (3 levels: No vs. Low vs. High) as fixed effect. Intercepts for subjects and items were included as random effects. Our results indicated no significant main effect of Syllabic Ambiguity, neither for children, $\chi^2(2) = 0.17$, $p = .918$, nor for adults, $\chi^2(2) = 1.48$, $p = .478$. In both age groups, WOD was numerically lower for the Low and High syllabic ambiguity condition (KUGEL and KUHLE items, respectively) than for the No syllabic ambiguity condition (KUNDE items). The results from this analysis are presented in Table 2.

4. Discussion

Previous research on handwritten language production suggests that both developing and skilled writers break words into smaller linguistic units such as syllables. However, the few studies that investigated syllabic processing in handwriting production in German have yielded an inconsistent pattern of results from a developmental perspective. Further, there has been some inconsistency in the findings with regards to the nature of syllabic processing effects. In the present study, we manipulated syllabic ambiguity, a characteristic of the German language, to investigate the role and nature of syllables in handwritten word production in children and

Table 2
Back-Transformed Estimated Writing Onset Duration (ms) per Syllabic Ambiguity for Children and Adults.

DV: WOD	Syllabic Ambiguity		
	No < CVC.CV >	Low < CV.CVC >	High < CVX.CV >
Children	1740	1725	1718
Adults	1165	1137	1115

Note. Dependent variable (DV). Consonant (C), vowel (V), silent consonant or vowel (X).

adults. Participants were asked to copy five-letter disyllabic words from a computer screen to pen tablets. Handwriting production was recorded with high spatiotemporal resolution and productions were analyzed in terms of Mean Stroke Duration and Writing Onset Duration. Our results offer support for the idea that syllables are functional units of handwritten word production in German children and adults, and that syllabic processing is phonological in nature.

We hypothesized that if syllables are functional units in handwriting, MSD should increase at the onset of the second syllable in syllabically unambiguous words with two intervocalic consonants, that is, at /d/ in a word like KUNDE, or at the middle consonant in syllabically ambiguous words with a single intervocalic consonant, that is, at /g/ in a word like KUGEL. For highly syllabically ambiguous words with a silent letter at the syllable boundary, such as KUHLE, we hypothesized that increases in MSD should occur on the silent letter (i.e., H), hence where the phonological onset of the second syllable /l/ is, rather than on the first letter of the second syllable (i.e., L), hence where the orthographic onset of the second syllable is. Indeed, our results showed increases in MSD at the onset of the second syllable in items of the No syllabic ambiguity condition (e.g., D in KUN.DE), and at the middle consonant in items of the Low syllabic ambiguity condition (e.g., G in KU.GEL). In items of the High syllabic ambiguity condition, we observed an increase in MSD at the silent letter (e.g., H in KUH.LE). These results are in agreement with previous findings in French, Spanish, Catalan, and Dutch, both in developmental (e.g., Kandel et al., 2011; Kandel & Soler, 2010; Kandel & Valdois, 2006a, 2006b) and adult handwriting production research (e.g., Bogaerts et al., 1996). Movement delays at the syllable onsets are thought to reflect increases in processing load due to activation of the second syllable, in parallel to motor execution of the second syllable's first letter (e.g., Kandel et al., 2011). The same results were obtained from both children and adults, thus offering support for the idea that syllables are functional units in handwriting production in German.

One surprising result in the adult data was the inflated MSD on the nucleus of the second syllable in items of the No and Low syllabic ambiguity condition (e.g., E in KUN.DE and E in KUGEL, respectively). We believe that this was due to the complexity of the letter E, which occurred in most stimuli in these particular positions. Motor programming as defined by van Galen et al. (1986) involves finding the correct sequence of strokes that correspond to an allograph, adjusting the overall force level, and recruiting the appropriate muscle groups. Van Galen et al. (1986) assume that motor programming demands increase with increasing trajectory length. The production of the letter E requires four strokes and additional in-air movements. Hence, MSD for this letter was inflated, independently of its within-word position. The reason why the same was not observed in the children data of these items was because syllabic processing effects are likely more robust in children than in adults. As a result, the production of the onset of the second syllable yielded considerably longer MSD than the production of the following complex letter E in children.

Our items in the High syllabic ambiguity condition had conflicting phonological and orthographic representations (e.g., KUHLE where there is no one-to-one phoneme-to-grapheme mapping in spelling; i.e., /CV.CV/, but <CVX.CV>). From a phonological perspective, the phonological onset of the second syllable occurs at the third position, that is, where the silent letter is encountered. We hypothesized that competition might arise between the two types of representations, slowing down motor execution during the production of the silent letter at the third position (i.e., H in KUHLE). Indeed, this is what we observed in our data. However, the phonological onset may then trigger the activation of the second syllable, which likely facilitates syllabic processing, and therefore masking potential additional syllabic processing delays at the fourth letter position (i.e., L in KUHLE). Indeed, in our data, the MSD between the third and the fourth letter (i.e., H and L in KUHLE) remained the same in children and adults, thus indicating similar processing delays on the silent letter and the onset of the second syllable. These results indicate that syllabic effects in German are phonological in nature.

With regards to previous findings from German, our results are consistent with the results from a study carried out by Nottbusch (2008), in which syllabic effects on handwritten word production were observed in German children aged between 11 and 13 years, and partly consistent with the results from a study by Weingarten (1998), in which syllabic effects on handwritten word production were obtained with adults, but not with second, fourth, and seventh graders, who typically range between 7 and 8, 9 and 10, and 12 and 13 years. However, as we have already mentioned earlier, the latter study had some methodological issues, which could explain the discrepancy between Weingarten's (1998) findings and Nottbusch's (2008) and our results. In our study, children and adults showed the same pattern of results, which suggests that syllabic effects on handwriting are not modulated by writing proficiency. We acknowledge, however, that this finding needs to be taken with caution due to the small adult sample size in our study. Critically, the syllabic effects on handwriting that we observed in the German children complement the findings from similar research conducted in Catalan, French, and Spanish. Further, our findings are in agreement with Nottbusch's (2008) and Weingarten's (1998) assumption that writers activate phonological representations of the words to-be-spelled. The discrepancy between the results by Kandel et al. (2009) and the results from the German studies, including the present study, are likely due to differences in the phoneme-to-grapheme mapping associations in the two languages. German has more transparent mappings than French, thus non-overlapping orthographic and phonological representations are more marked in the former language, which may make writers more sensitive to them.

Interestingly, according to the Kandel and Spinelli (2010) framework, the second and third letters in the items of the High syllabic ambiguity condition (i.e., UH in KUHLE) could be thought to represent a complex grapheme. Complex grapheme retrieval may increase processing load and thus slow down motor execution at the preceding consonant (i.e., K) and vowel (e.g., U), when compared to simple graphemes, such as the vowel in items like KUNDE or KUGEL. From a linguistic perspective, however, it is under debate whether the <VX> sequences in our stimuli correspond to complex graphemes. According to Eisenberg (2013), there are only simple vowel graphemes in German. Further, silent letters, which function as "lengthening markers" in reading, are thought to have simple grapheme status too (Noack, 2002, p. 150). In our analyses, MSD for letter positions 1 and 2 were not different across conditions (children, Letter Position 1: No vs. High syllabic ambiguity condition, $t = -0.30$, $p = 0.762$; Low vs. High syllabic ambiguity condition, $t = 0.34$, $p = 0.737$; Letter Position 2: No vs. High syllabic ambiguity condition, $t = -0.24$, $p = 0.814$; Low vs. High syllabic ambiguity condition, $t = -0.09$,
$p = 0.927$; adults, Letter Position 1: No vs. High syllabic ambiguity condition,
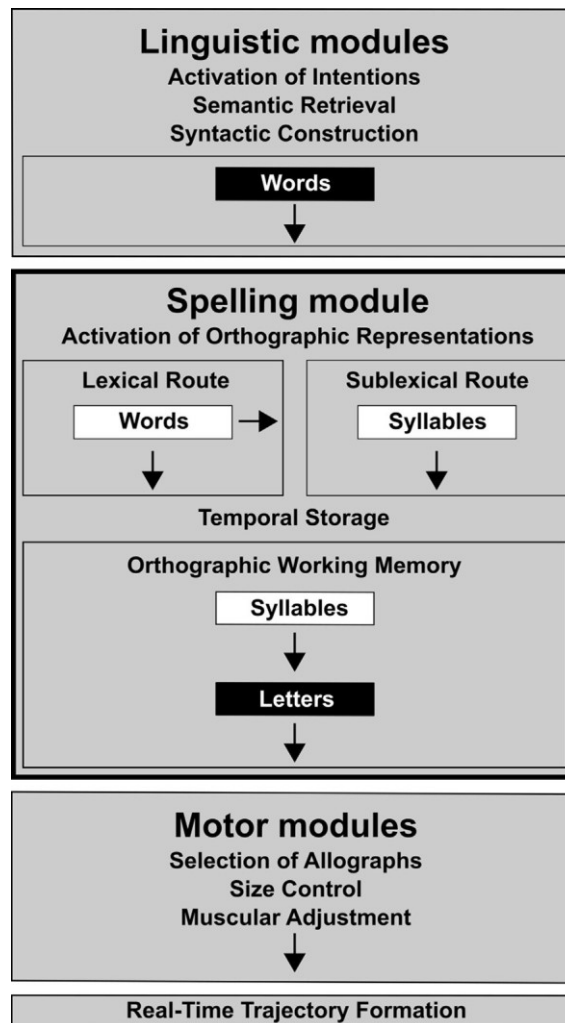
Fig. 1. A revision of van Galen's (1991) and Kandel et al.'s (2011) handwriting production models, which is proposed on the basis of the present findings and focuses on the linguistic units that are thought to be processed in the spelling module.

$t = -0.15$, $p = 0.879$; Low vs. High syllabic ambiguity condition, $t = -0.84$, $p = 0.404$; Letter Position 2: No vs. High syllabic ambiguity condition, $t = -0.28$, $p = 0.780$; Low vs. High syllabic ambiguity condition, $t = -0.40$, $p = 0.691$). Thus, our results support the idea that silent letters in German are processed as simple graphemes.

We hypothesized that if syllabic ambiguity does not influence WOD, then the Low and High syllabic ambiguity condition should yield lower values than the No syllabic ambiguity condition. In contrast, if syllabic ambiguity influences WOD, then the Low and High syllabic ambiguity condition should yield higher values than the No syllabic ambiguity condition. Our analyses showed no significant main effect of Syllabic Ambiguity, neither for children nor for adults. The reason for this could be because the items in the Low and High syllabic ambiguity condition comprised shorter first syllables, yet, their syllabic ambiguity inflated their WODs, thus making the values of this measure similar to those of items with longer first syllables (namely, the items in the No syllabic ambiguity condition). This result indicates indeed an ambiguity effect; however, such effect may be not as robust, thus yielding similar WODs across conditions. Kandel and Perret (2015b) and Roux et al. (2013) also failed to find significant WOD differences between items with and items without conflicting orthographic and phonological representations, yet significant MSD differences were observed at the letter positions where the conflict occurred.

Our results have implications for extant models of handwriting production. Our findings show that German children and adults process syllables during handwriting, and that syllabic processing is phonological in nature. In agreement with van Galen (1991), we propose that word units from the conceptual level form the input to the spelling module (see Fig. 1, 'linguistic modules') and that the spelling module activates letter units (see Fig. 1, 'spelling module'), which in turn form the input to the motor level. According to Kandel et al. (2011), writers activate word-sized orthographic representations (see Fig. 1, 'lexical route'). These are then stored and processed in orthographic working memory, so that syllables and then letter units become activated (see Fig. 1, 'orthographic working memory'). Findings from the handwritten word production domain (e.g., Kandel et al., 2017; Kandel & Perret, 2015b;

Nottbusch, 2008; Roux et al., 2013; Weingarten, 1998) and the present study, however, suggest that phonological representations are likely to become activated too. This might be done via lexical (see Fig. 1, 'lexical route') or, in a spelling-to-dictation and a copy task additionally, via nonlexical access. Importantly, a sublexical route would then convert linguistic units of different grain sizes such as syllables from phonology to orthography (see Fig. 1, 'sublexical route'). These units would form input to orthographic working memory too. Output from lexical and sublexical spelling routes would then be integrated at the orthographic working memory level. As previously shown (Kandel & Perret, 2015b; Roux et al., 2013), integration of outputs in items with conflicting orthographic and phonological representations may be not completed before writing onset, but may cascade into motor production. The final spelling decision may be then made at the conflicting position, which may further modulate motor production.

To write an item without syllabic ambiguity (e.g., KUNDE), writers may either activate its orthographic word representation via the lexical route (i.e., KUNDE), or convert it syllable by syllable from phonology to orthography via the sublexical route (i.e., KUN, DE). Critically, both types of representation match and no conflict occurs. Before writing onset, the syllable module activates the first syllable, which is KUN for both spelling routes. The second syllable DE becomes activated online at its onset, which increases movement duration at this letter position due to parallel processing at the spelling and the motor level for both types of representation. To write an item with syllabic ambiguity (e.g., KUGEL or KUHLE), writers may activate its orthographic word representation via the lexical route (i.e., KUGEL or KUHLE, respectively), or convert it from phonology to orthography via the sublexical route. Critically, syllabic ambiguity may result in sublexical output that conflicts with the corresponding orthographic representation. First, in items of the Low syllabic ambiguity condition, the sublexical route may generate KU and GEL, or, KUG and GEL, respectively, so that a conflict may occur after the second letter (i.e., after U) due to the special status of the single intervocalic consonant. Second, in items of the High syllabic ambiguity condition, the sublexical route is likely to generate KU and LE, so that a conflict occurs after the second letter (i.e., after U) due to the presence of a silent letter. The output is temporally stored and further processed in orthographic working memory. Before writing onset, the syllable module activates the first syllable KU from KU.GEL or KUH from KUH.LE, respectively, via the lexical (orthographic) route or the first syllable as described above via the sublexical route. During the production of the third letter, a conflict must be resolved in both conditions and the second syllable is likely to be activated, which increases letter duration at this letter position due to parallel processing at the spelling and the motor level. As mentioned earlier, in case of the High syllabic ambiguity condition, we believe that conflict resolution at the silent letter position may further facilitate activation of the second syllable.

In conclusion, our study used a set of tightly-controlled experimental stimuli to investigate syllabic processing effects in handwriting production in the German language. Our work contributes to the empirical evidence in handwriting research, showing that cognitive processes in spelling cascade into motor production, that syllables are functional units in both developmental and skilled handwriting, and that the nature of syllabic processing is phonological, at least as far as the German language is concerned.

5. Author note

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Appendix. Materials

Syllabic Ambiguity		
No < CVC.CV >	Low < CV.CVC >	High < CVX.CV >
BIRNE	BIBER	BIENE
FARBE	FADEN	FAHNE
HARFE	HAFEN	HAARE
KERZE	KEGEL	KEHLE
KUNDE	KUGEL	KUHLE
LINSE	LITER	LIEBE
MILDE	MINUS	MIETE
SALBE	SALAT	SAHNE
TINTE	TIGER	TIEFE
WANZE	WAGEN	WAAGE

Note: Consonant letter (C), vowel letter (V), silent consonant or vowel letter (X).

References

Álvarez, C. J., Cottrell, D., & Afonso, O. (2009). Writing dictated words and picture names: Syllabic boundaries affect execution in Spanish. *Applied Psycholinguistics*, *30*, 205–223. https://doi.org/10.1017/S0142716409090092.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*, 1–48. https://doi.org/10.18637/jss.v067.i01.

Bogaerts, H., Meulenbroek, R. G. J., & Thomassen, A. J. (1996). The possible role of the syllable as a processing unit in handwriting. In M. L. Simner, C. G. Leedham, & A. J. Thomassen (Eds.). *Handwriting and drawing research: Basic and applied issues* (pp. 115–126). Amsterdam, The Netherlands: IOS Press.

Bonin, P., Méot, A., Lagarrigue, A., & Roux, S. (2015). Written object naming, spelling to dictation, and immediate copying: Different tasks, different pathways? *The Quarterly Journal of Experimental Psychology, 68*, 1268–1294. https://doi.org/10.1080/17470218.2014.978877.

Eisenberg, P. (2013). Grundriss der deutschen Grammatik: Band 1. Das Wort [Outline of the German grammar: Vol. 1. The word] (4th ed.). doi:10.1007/978-3-47600757-5.

Fox, J., & Weisberg, S. (2011). *An R companion to applied regression* (2nd ed.). Thousand Oaks, CA: Sage.

Guinet, E., & Kandel, S. (2010). Ductus: A software package for the study of handwriting production. *Behavior Research Methods, 42*, 326–332. https://doi.org/10.3758/BRM.42.1.326.

Hothorn, T., Bretz, F., Westfall, P., Heiberger, R. M., Schuetzenmeister, A., & Scheibe, S. (2016). Package 'multcomp': Simultaneous inference in general parametric models. Retrieved from https://cran.r-project.org/web/packages/multcomp/multcomp.pdf.

Houghton, G., & Zorzi, M. (2003). Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology, 20*, 115–162. https://doi.org/10.1080/02643290242000871.

Kandel, S. (2009). For a psycholinguistic approach of handwriting production. In A. Vinter, & J.-L. Velay (Eds.). *Advances in graphonomics: Proceedings of the 14th biennial conference of the International Graphonomics Society 2009* (pp. 83–86). Fontaine les Dijon, France: Imprimerie Vidonne.

Kandel, S., Álvarez, C. J., & Vallée, N. (2006). Syllables as processing units in handwriting production. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 18–31. https://doi.org/10.1037/0096-1523.32.1.18.

Kandel, S., Hérault, L., Grosjacques, G., Lambert, E., & Fayol, M. (2009). Orthographic vs. phonologic syllables in handwriting production. *Cognition, 110*, 440–444. https://doi.org/10.1016/j.cognition.2008.12.001.

Kandel, S., Peereman, R., & Ghimenton, A. (2013). Further evidence for the interaction of central and peripheral processes: The impact of double letters in writing English words. *Frontiers in Psychology, 4*, 1–8. https://doi.org/10.3389/fpsyg.2013.00729.

Kandel, S., Peereman, R., & Ghimenton, A. (2014). How do we code the letters of a word when we have to write it? Investigating double letter representation in French. *Acta Psychologica, 148*, 56–62. https://doi.org/10.1016/j.actpsy.2014.01.002.

Kandel, S., Peereman, R., Ghimenton, A., & Perret, C. (2017). Letter coding affects movement production in word writing: An English-Italian cross-linguistic study. *Reading and Writing*. https://doi.org/10.1007/s11145-017-9756-y Advance online publication.

Kandel, S., Peereman, R., Grosjacques, G., & Fayol, M. (2011). For a psycholinguistic model of handwriting production: Testing the syllable-bigram controversy. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 1310–1322. https://doi.org/10.1037/a0023094.

Kandel, S., & Perret, C. (2015a). How do movements to produce letters become automatic during writing acquisition? Investigating the development of motor anticipation. *International Journal of Behavioral Development, 39*, 113–120. https://doi.org/10.1177/0165025414557532.

Kandel, S., & Perret, C. (2015b). How does the interaction between spelling and motor processes build up during writing acquisition? *Cognition, 136*, 325–336. https:// doi.org/10.1016/j.cognition.2014.11.014.

Kandel, S., & Soler, O. (2010). Differential syllable effects when learning to write French and Catalan words. Retrieved from *Current Psychology Letters, 25*(3), 1–13. http://cpl.revues.org/4965.

Kandel, S., Soler, O., Valdois, S., & Gros, C. (2006). Graphemes as motor units in the acquisition of writing skills. *Reading and Writing, 19*, 313–337. https://doi.org/10.1007/s11145-005-4321-5.

Kandel, S., & Spinelli, E. (2010). Processing complex graphemes in handwriting production. *Memory & Cognition, 38*, 762–770. https://doi.org/10.3758/MC.38.6.762.

Kandel, S., Spinelli, E., Tremblay, A., Guerassimovitch, H., & Álvarez, C. J. (2012). Processing prefixes and suffixes in handwriting production. *Acta Psychologica, 140*, 187–195. https://doi.org/10.1016/j.actpsy.2012.04.005.

Kandel, S., & Valdois, S. (2006a). French and Spanish-speaking children use different visual and motor units during spelling acquisition. *Language and Cognitive Processes, 21,* 531–561. https://doi.org/10.1080/01690960500095946.

Kandel, S., & Valdois, S. (2006b). Syllables as functional units in a copying task. *Language and Cognitive Processes, 21*, 432–452. https://doi.org/10.1080/01690960400018378.

Meulenbroek, R. G. J., & van Galen, G. P. (1990). Perceptual-motor complexity of printed and cursive letters. Retrieved from *The Journal of Experimental Education, 58*(2), 95–110. http://www.jstor.org/stable/20151799.

Miceli, G., & Costa, V. (2014). The role of lexical and sublexical orthography in writing: Autonomy, interactions, and neurofunctional correlates. In P. E. Nathan (Ed.). *Oxford Library of Psychology. The Oxford handbook of language production* (pp. 358–378). New York, NJ: Oxford University Press.

Noack, C. (2002). Regularities in German orthography: A computer-based comparison of different approaches to sharpening. In H. Altmann, P. Blumenthal, H. J. Heringer, I. Plag, H. Vater, & R. Wiese (Eds.). *Linguistische Arbeiten: Vol. 460. The relation of writing to spoken language* (pp. 149–168). Tübingen, Germany: Niemeyer.

Nottbusch, G. (2008). *Handschriftliche Sprachproduktion: Sprachstrukturelle und ontogenetische Aspekte [Handwritten language production: Linguistic and ontogenic aspects]*. Tübingen, Germany: Niemeyer.

Rapp, B., & Fischer-Baum, S. (2014). Representation of orthographic knowledge. In P. E. Nathan (Ed.). *Oxford Library of Psychology. The Oxford handbook of language production* (pp. 338–357). New York, NJ: Oxford University Press.

Rapp, B., Purcell, J., Hillis, A. E., Capasso, R., & Miceli, G. (2016). Neural bases of orthographic long-term memory and working memory in dysgraphia. *Brain, 139*, 588–604. https://doi.org/10.1093/brain/awv348.

Roux, S., McKeeff, T. J., Grosjacques, G., Afonso, O., & Kandel, S. (2013). The interaction between central and peripheral processes in handwriting production. *Cognition, 127*, 235–241. https://doi.org/10.1016/j.cognition.2012.12.009.

Schroeder, S., Würzner, K.-M., Heister, J., Geyken, A., & Kliegl, R. (2015). childLex: A lexical database of German read by children. *Behavior Research Methods, 47*, 1085–1094. https://doi.org/10.3758/s13428-014-0528-1.

Soler Vilageliu, O., & Kandel, S. (2012). A longitudinal study of handwriting skills in pre-schoolers: The acquisition of syllable oriented programming strategies. *Reading and Writing, 25*, 151–162. https://doi.org/10.1007/s11145-010-9251-1.

van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science, 10*, 165–191. https://doi.org/10.1016/0167-9457(91)90003-G.

van Galen, G. P., Meulenbroek, R. G. J., & Hylkema, H. (1986). On the simultaneous processing of words, letters and strokes in handwriting: Evidence for a mixed linear and parallel model. In G. E. Stelmach, & P. A. Vroon (Eds.). *Advances in Psychology: Vol. 37. Graphonomics: Contemporary research in handwriting* (pp. 5–20). https://doi.org/10.1016/S0166-4115(09)60068-6.

Weingarten, R. (1998). Schreibprozesse im Schriftspracherwerb [Writing processes during literacy acquisition]. In R. Weingarten, & H. Günther (Eds.). *Schriftspracherwerb* (pp. 62–81). *[Literacy acquisition]*. Baltmannsweiler, Germany: Schneider Verlag Hohengehren.

Wiese, R. (2000). *The phonology of German*. Oxford, England: Oxford University Press (Original work published 1996).

Yarkoni, T., Balota, D., & Yap, M. (2008). Moving beyond Coltheart's N: A new measure of orthographic similarity. *Psychonomic Bulletin and Review, 15*, 971–979. https://doi.org/10.3758/PBR.15.5.971.