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Morphological processing in developmental handwriting production: evidence from kinematics

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Abstract

In this study, we investigated effects of morphological processing on handwriting production in beginning writers of German. Children from Grades 3 and 4 were asked to copy words from a computer screen onto a pen tablet, while we recorded their handwriting with high spatiotemporal resolution. Words involved a syllable-congruent visual disruption (e.g., "Gol**fer**"), a morpheme-congruent visual disruption (e.g., "Golf**er**"), or had no disruption (e.g., "Golfer"). We analyzed productions in terms of Writing Onset Duration and Letter Duration at the onset of the second syllable ("f" in "Gol.fer") and the onset of the suffix ("e" in "Golf_er"). Results showed that durations were longer at word-writing onset only for words with a morpheme-congruent visual disruption. Also, letter durations were longer at the onset of the second syllable (i.e., "-fer") and shorter at the onset of the suffix (i.e., "-er") only for words with a syllable-congruent visual disruption. We interpret these findings within extant theories of handwriting production and offer an explanation for the observed effects before and during trajectory formation.

Keywords Handwriting production · Spelling · Syllables · Morphemes · Kinematics

When writing words, children come across linguistic units of different grain sizes, such as syllables, morphemes, and graphemes or letters. However, the relative

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weight assigned to such units in formal spelling instruction differs as a function of orthography and the educational approach adopted by each country. For example, children in Germany are typically taught phoneme-to-grapheme correspondences first (see, e.g., Landerl & Thaler, 2013, for an overview). However, German spelling is modulated by syllabic and morphological principles (e.g., Eisenberg, 2013), and so some more recent educational approaches in Germany tend to focus on syllables and morphemes from the beginning of formal literacy instruction (e.g., Röber, 2009).

Kinematic studies on handwriting production have shown that writers change movement duration in the course of word production systematically (see, e.g., van Galen, 1991, for an overview). For example, in studies, which investigated influences of syllabic structure on handwriting production, writers of different languages slowed down between syllables or at syllable onsets. This included writers of Romance languages, such as French (Kandel & Soler, 2010; Kandel et al., 2006a, 2006b, 2011; Kandel & Valdois, 2006a, 2006b), Catalan (Kandel & Soler, 2010; Soler Vilageliu & Kandel, 2012), and Spanish (Álvarez et al., 2009), as well as writers of Germanic languages, such as German (Hess et al., 2019; Nottbusch, 2008; Weingarten, 1998) and Dutch (Bogaerts et al., 1996). These findings offer support for the idea that syllables are functional units of writing.

According to a prominent model of handwritten word production (Kandel et al., 2011), writers activate word-sized orthographic representations, which in turn activate syllables and then graphemes prior to motor programming. More specifically, the first syllable is assumed to be retrieved before word-writing onset, while subsequent syllables are activated online. Based on van Galen's (1991) idea of parallel processing, one prediction derived from Kandel et al.'s (2011) model would be that activation of the corresponding syllabic unit in parallel to trajectory formation would increase processing load and, accordingly, would delay movement execution at syllable boundaries (see Kandel et al., 2006a, 2006b, for a similar prediction). In the present study, we applied this logic to morphological boundaries, where the empirical evidence on developmental (Breadmore & Deacon, 2019; Quémart & Lambert, 2019; Suárez-Coalla et al., 2017) and skilled handwriting production (Afonso & Álvarez, 2019; Kandel et al., 2008, 2012) is rather limited. Furthermore, the available results tend to be inconsistent with regard to (a) the point in time when effects occur and (b) the direction of the effects when they occur prior to word-writing onset.

Morphological processing in handwriting production

In the developmental domain, studies in English, Spanish, and French have been carried out. English children aged between 6 and 11 years were found to start writing bimorphemic words (e.g., "rock_ing"[1] or "rock_y") and their corresponding monomorphemic base words (e.g., "rock") faster than monomorphemic control

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[1] Underscores indicate morphological boundaries.

words (e.g., "rocket"; Breadmore & Deacon, 2019). Spanish children aged between 7 and 12 years were also found to start writing bimorphemic words and pseudowords (e.g., "PEL_UDO", hairy, or "PEL_ERA", respectively) faster than monomorphemic control words and pseudowords (e.g., "PAGANA", pagan, or "PEMURA", respectively; Suárez-Coalla et al., 2017). In contrast, French 10- and 12-year-old children (Quémart & Lambert, 2019) did not show differences in writing onset duration between bimorphemic (e.g., "ferm_ier", farmer) and monomorphemic control words (e.g., "formule", formula, or "chemise", shirt), whereas the corresponding adult sample in the same study started writing the former items faster than the latter. Also, 10-year-old children in the same study produced the relevant letter (e.g., "r") slower when it preceded a syllable onset in monomorphemic words, such as "m" in "for.mule",[2] than when it preceded a syllable onset in bimorphemic words, such as "m" in "fer.m_ier". Then, 12-year-old children and adults produced the relevant letter (e.g., "m") slower when it preceded a morpheme onset, such as "i" in "ferm_ier", than when the same letter corresponded to a non-morphemic onset, such as "i" in the monomorphemic word "chemise". Thus, results from studies with English (Breadmore & Deacon, 2019) and Spanish (Suárez-Coalla et al., 2017) children suggest that morphological effects occur prior to word-writing onset, while results from French 12-year-old children (Quémart & Lambert, 2019) indicate that morphological effects occur during writing. Only the French adults showed effects on early and late measures of handwriting production, while the direction of the effects was in line with what has been observed in children (i.e., speedup before word-writing onset; delay during writing).

It is worth noting, however, that the direction of the effects of morphological processing on early measures of handwriting production, such as writing onset duration, varies when further empirical evidence from kinematic studies on skilled handwriting production is considered. For example, in a study by Kandel et al. (2008), French adult writers took more time to start writing suffixed words (e.g., "boul_ette", little ball) than pseudo-suffixed words (e.g., "goélette", schooner). As far as trajectory formation is concerned, writers slowed down at the morpheme boundary in suffixed words (i.e., between "l" and "e" in "boul_ette") relative to the corresponding letter boundary in pseudo-suffixed words (i.e., between "l" and "e" in "goélette"), as indicated by Inter-Letter Interval Duration. In another study, Afonso and Álvarez (2019) asked Spanish adults to write compounds. In Exp. 3, they manipulated the frequency of the second morphological constituent (e.g., "PEDRERO" in "PICA_PEDRERO", stonecutter, vs. "PAPELES" in "PISA_PAPELES", paperweight, where "pedrero" is a low-frequency word and "papeles" a high-frequency one). The frequency of the first constituent and the whole compound were controlled for. Participants took longer to start writing compounds with a low-frequency second constituent. In addition, participants produced the inter-letter interval that preceded the last letter of the first constituent slower in words with a low-frequency second constituent. Thus, results from a study with adults by Quémart and Lambert (2019) suggest that morphological processing speeds up word-writing onset, whereas results from studies

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[2] Dots indicate syllabic boundaries.

with adults by Kandel et al. (2008) and Afonso and Álvarez (2019) indicate that morphological processing slows down word-writing onset. Across all three experiments, however, writers slowed down during trajectory formation (see also Kandel et al., 2012, for converging empirical evidence).

To accommodate the findings, Quémart and Lambert (2019) used the model of Kandel et al. (2011) as a base and proposed that the orthographic lexicon could be organized around morphemes (see also Rapp & Fischer-Baum, 2014, for an overview), so that writers would activate morphological constituents first, and then syllables and letters. More specifically, morphological constituents are thought to be accessed in a serial order (Kandel et al., 2008). In the case of suffixed words then, writers would access the stem prior to word-writing onset, and then the suffix, while writing onset duration should increase as a function of the number of morphological constituents. On the assumption that writers activate one constituent after the other in a serial order (Kandel et al., 2008), writing onset duration should be longer in bimorphemic words (e.g., "boul_ette") than in pseudo-suffixed words (e.g., "goélette"). In contrast, on the assumption that writers activate *only* the first constituent prior to word-writing onset (Quémart & Lambert, 2019), writing onset duration should be shorter in bimorphemic words than in pseudo-suffixed words. According to Quémart and Lambert (2019), subsequent morphological constituents (i.e., "ette" in "boulette") are thought to be activated online, thus slowing down writers at the morphological boundary due to cognitive processing at the spelling level, which occurs in parallel to motor execution. It is worth highlighting that the results obtained by Afonso and Álvarez (2019, Exp. 3) and Kandel et al. (2008) suggest that writers slow down during trajectory formation even when they access both morphological constituents prior to word-writing onset. Crucially, according to Afonso and Álvarez (2019), writers need to further activate or reactivate the second morphological constituent online, which may slow down trajectory formation due to parallel orthographic processing and motor execution. This is compatible with empirical data provided by Lambert et al. (2008), which show that activated orthographic representations may fade in short-term memory, and therefore may need to be refreshed when there is a long delay between stimulus presentation and word-writing onset. Taken together, determining when and how morphological structure influences handwriting production is critical for the further development of theoretical models of handwritten language production (see, e.g., Levesque et al., 2021, for a similar point).

Present study

In the present study, we tested these ideas by investigating whether the morphological structure of printed words influences handwriting production in German children aged between 7 and 11 years (Grades 3 and 4). Morphological processing is prominent in the German language (e.g., Eisenberg, 2013; Fuhrhop, 2009). More specifically, in the German writing system, phonological principles may be modulated by morphological principles. For example, word forms, such as "Kin**d**er" (children; /

kɪndəʀ/, < kinder >)[3] or "richti**ge**" (correct; /rɪçtigə/, < richtige >), maintain their spellings in morphologically related word forms, even though their phonological word forms differ due to "final devoicing" or "spirantization," such as "Kin**d**" (child; /kɪnt/, but < kind >) or "richti**g**" (correct; /rɪçtɪç/, but < richtig >). Thus, morphological principles play an important role in German, as they facilitate visual word recognition; yet, some of them may also increase ambiguity in spelling (e.g., Eisenberg, 2013; Fuhrhop, 2009). Children in these age groups were chosen, because beginning writers of German are explicitly taught about morphological principles from Grade 3 onwards, at least as far as the curriculum of the federal state of Berlin is concerned (Landesinstitut für Schule und Medien Berlin-Brandenburg, 2015). Children are also encouraged to use morphological information implicitly, e.g., by deriving spellings from known words, before Grade 3. As such, we expected third and fourth graders to be at the orthographic stage (Scheerer-Neumann, 2018), thus making use of morphemes during handwriting production, at least when they are explicitly pointed to the morphological structure of printed words.

Studies on the influence of morphological structure on handwriting behavior have typically used spelling-to-dictation or copy tasks (e.g., Breadmore & Deacon, 2019; Quémart & Lambert, 2019; Suárez-Coalla et al., 2017). Another relevant task, which has been primarily used in the reading domain, involves the visual disruption paradigm. According to this paradigm, readers are presented with words that contain a visual disruption, such as a blank space (e.g., "ma lade", ill; Colé et al., 2011), a hyphen (e.g., "ta-lo", house; Häikiö et al., 2015), a colon (e.g., "FAH:RER", driver; Hasenäcker & Schroeder, 2017), or a change of font color (e.g., "carton", cardboard; Chetail & Mathey, 2009). Independently of the type of visual disruption used, words are typically segmented into linguistic units, such as syllables (e.g., "Gol**fer**", golfer) or morphemes (e.g., "Golf**er**"). This paradigm is based on the idea that a visual disruption facilitates reading if the corresponding segmentation makes units that are thought to be activated in reading more salient, yet it inhibits reading if such segmentation masks the salience of these units (e.g., Hasenäcker & Schroeder, 2017). Indeed, the empirical evidence shows that beginning readers may speed up processing in syllable-congruent visual disruption conditions (e.g., Chetail & Mathey, 2009; Hasenäcker & Schroeder, 2017). As such, we reasoned that the visual disruption paradigm might be a means to point beginning writers explicitly to the morphological structure of printed words. Accordingly, we asked children to copy from a computer screen items that were manipulated as per this paradigm, while we recorded their handwritten productions with high spatiotemporal resolution.

Our experimental conditions included words with a morpheme-congruent visual disruption (e.g., "Golf**er**"), words without visual disruption (e.g., "Golfer"), and words with a syllable-congruent visual disruption (e.g., "Gol**fer**"), as syllabic effects are typically robust in beginning writers (e.g., Hess et al., 2019). Moreover, the latter condition allowed us to directly compare the role of morphemes and syllables in developmental handwriting production. We hypothesized that the use of a morpheme-congruent (e.g., "Golf**er**") and a syllable-congruent visual disruption

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[3] Slashes and angle brackets indicate phonological and orthographic representations, respectively.

condition (e.g., "Gol**fer**") would facilitate the activation of the corresponding units (i.e., morphemes or syllables, respectively). Within a dual-route framework of handwriting production (e.g., Bonin et al., 2015), orthographic representations of the words to-be-spelled are either accessed via a lexical route through mentally-stored lexical representations, which could be organized in terms of morphemes (e.g., Quémart & Lambert, 2019; Rapp & Fischer-Baum, 2014), or assembled via a sublexical route by means of phonology-to-orthography conversion processes. Syllables are thought to be activated via the sublexical route (e.g., Hess et al., 2019; Miceli & Costa, 2014). Both routes are considered to be active in parallel and to interact during writing (e.g., Kandel & Perret, 2015; Roux et al., 2013). Based on this idea, we hypothesized that writing behavior in the two conditions would be different, especially at the onset of the relevant unit (i.e., syllable or morpheme, respectively).

Furthermore, the no disruption condition ("Golfer") allowed us to investigate which of the two routes is likely to be used by children when no unit is highlighted. If writing behavior in this condition is similar to the morpheme-congruent visual disruption condition, this would indicate that writers must activate the lexical route during normal writing. If, by contrast, writing behavior in the no disruption condition is similar to the syllable-congruent visual disruption condition, this would indicate that writers standardly activate the sublexical route when writing. As beginning writers at the orthographic stage in German might have a preference for sublexical processing (Scheerer-Neumann, 2018), we expected to observe the latter pattern, namely, similar writing behavior in the no disruption and the syllable-congruent visual disruption condition, which would suggest that children spell words without disruption ("Golfer") sublexically (e.g., via the syllables "Gol" and "fer").

In order to test these predictions, we compared all conditions against each other: In a first step, we compared the morpheme- and the syllable-congruent visual disruption conditions directly with each other. In a second step, we compared each of the two visual disruption conditions to the baseline, that is, the no disruption condition.

We measured handwritten word production in terms of Writing Onset Duration and Letter Duration at the syllable and morpheme onsets. We opted for measuring at these two positions, because inhibitory effects of syllabic processing have been observed on the inter-letter interval preceding a syllable onset (e.g., Álvarez et al., 2009; Kandel et al., 2006a), as well as on the syllable onset itself (e.g., Bogaerts et al., 1996; Kandel et al., 2006b). Furthermore, inhibitory effects of morphological processing have been observed on the inter-letter interval preceding the morpheme onset when writing in printed script (Kandel et al., 2008). We predicted that the no disruption and the syllable-congruent visual disruption conditions would yield longer Letter Durations at the syllable onset (e.g., "f" in "Golfer" and "Gol**fer**", respectively) compared to the morpheme-congruent visual disruption condition, because syllables would be activated in parallel to motor execution. The opposite pattern should be observed at the morpheme onset, namely longer Letter Duration in items of the morpheme-congruent visual disruption condition (e.g., "e" in "Golf**er**") relative to the other two conditions, because morphemes would be activated in parallel to motor execution. However, the effects of syllabic and morphological processing on early measures of handwriting production, such as Writing Onset Durations,

have yielded less consistent results (see, e.g., Hess et al., 2019; Sausset et al., 2012, for syllabic effects; and Kandel et al., 2008; Quémart & Lambert, 2019, for morphological effects). Thus, our examination of whether highlighting syllabic or morphological information affects writing onset duration was exploratory in nature.

Method

Participants

One hundred and thirty-four children from Grade three and Grade four (66 in Grade 3 and 68 in Grade 4), recruited from ten classes (six in Grade 3 and four in Grade 4) of three state primary schools in Berlin, Germany, participated in the experiment for a small gift. Children (120 right-handed, 11 left-handed, 3 ambidextrous; 64 females) were on average 9.1 years old ($SD=0.6$, $Range=[7.6, 10.9]$). All participants reported to have learned German before the age of five.

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. Children gave oral informed consent, while written informed consent was obtained from their parents, both in accordance with the Declaration of Helsinki.

Materials

We selected 12 disyllabic word triplets (i.e., nouns) with an identical CV structure and an identical suffix, such as "Hefter" (folder), "Golfer" (golfer), and "Laster" (truck). Items and their characteristics were extracted from the childLex corpus (Version 0.16.03; Schroeder et al., 2015; see Appendix). Six word triplets, which were six-letters long, contained the "er" suffix, while the remaining six, which were seven-letters long, contained the "ung" suffix. Suffixes began with a vowel (i.e., "er" and "ung") and were combined with a stem. Syllable and morpheme boundaries did not overlap. Our syllabifications follow the Maximum Onset Principle (e.g., Kahn, 1976; Selkirk, 1982), whereby the phonological onset of the second syllable is maximized (e.g., "Teilung", division; /taɪ.lʊŋ/)[4]. Items' first syllable was three-letters long, while their second syllable was three- to four-letters long (e.g., "Gol.fer", or "Hei.zung", heater). As such, the onset of the second syllable was at letter position 4 across items. Furthermore, stems were four-letters long, while suffixes were either two- or three-letters long (e.g., "Golf_er", or "Heiz_ung"). As such, the onset of the suffix was at letter position 5 across items.

Target words either belonged to the no disruption condition (i.e., they were presented in black font color, e.g., "Golfer"), or to the morpheme-congruent visual

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[4] The syllabification of three items (i.e., "Festung", "Laster", and "Rüstung") according to the Maximum Onset Principle may not be apparent; however, it should be noted that the vowel of the first syllable in all these cases is short, and given that it is a closed syllable, the only possible syllabification is "Fes.tung", "Las.ter", and "Rüs.tung".

disruption condition (i.e., the stem was presented in black and the suffix in orange font color, e.g., "Golf**er**"),[5] or to the syllable-congruent visual disruption condition (i.e., the first syllable was presented in black and the second syllable in orange font color, e.g., "Gol**fer**"). We used the visual disruption by font color paradigm, because this type of visual disruption has been previously used in textbooks (e.g., Donth-Schäffer et al., 2013; Kuhn & Mrowka-Nienstedt, 2016). We opted for this paradigm, rather than using a disruption symbol (e.g., a colon or a hyphen) or a blank for example, because children could have tried to copy the disruption symbol or leave a blank between syllables and morphemes, thus potentially increasing trajectory length and duration of the units under investigation.

Procedure

Each target word of a triplet was assigned to one of three sets (e.g., "Hefter" set 1; "Golfer" set 2; "Laster" set 3). In turn, we assigned each of the three sets, which comprised twelve target words, to one of the three conditions that made up a list. We repeated this procedure three times. Thus, three lists were created with each target word appearing only once within a list, and once in each of the three visual disruption conditions across the three lists. A similar number of participants was assigned to each list. Twelve trials per visual disruption condition made a total of 36 trials per participant. The order of trial presentation within each list was randomized across participants.

Children were tested individually in a quiet room. Each target word was presented in 24-point Arial font on white background in the center of a 24-inch monitor screen. An auditory signal and a blank screen preceded each trial for 1,000 ms. The stimulus remained on the screen until children wrote down their response. They first received a response sheet with twelve lines (horizontal length of a line 170 mm; vertical distance between lines 12.5 mm), and then, they were given a Wacom Intuos4 Inking Pen and were asked to write down the presented word on a new line for each trial. Children 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 critical for developmental handwriting data. Only children who wrote in cursive ($N = 134$) were included in our analyses (for consistency, three children who wrote in print were excluded). Children were also asked to read the stimulus prior to writing onset, and to reread it during writing if and only if they had forgotten it. 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 per mm) and were controlled by Ecriture from the Ductus software package (Version 1.0.1.218; Guinet & Kandel, 2010).

Participants were familiarized with the pen and the writing surface by scribbling at the top of the response sheet and by writing down the word "Schule" (school)

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[5] Bold type appeared in (non-bold) orange font color in the printed stimulus words.

in response to dictation. They were then presented with the 36 experimental trials. Three practice trials preceded the experimental trials. After each trial, participants initiated the next trial by pressing the pen tip onto a blue trigger zone at the bottom right-handed corner of the tablet. The experimenter replaced the response sheet with a new one after the practice trials, as well as after every twelve 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 Open-HandWrite software package (Version 0.3.8; Simpson et al., 2018). In those cases where participants (a) gave an incorrect response or misspelled the word (10.8% of the data), or (b) corrected their response during the trial (12.3%), data were treated as errors and discarded from the analysis. This exclusion procedure ensured that differences in movement duration between conditions could not be attributed to differences in letter sequences between conditions (Lambert et al., 2012).

Writing Onset Duration and Letter Duration at the onset of the second syllable and at the onset of the suffix were calculated for the target words and used as dependent variables. Durations were expressed in milliseconds (ms). Writing Onset Duration was defined as the length of the time interval between stimulus onset on the screen and onset of word writing on the paper. Letter Duration at the onset of the second syllable and at the onset of the suffix were each defined as the length of the time interval between offset of writing the last stroke of the letter preceding the target letter (i.e., letter preceding onset of second syllable or suffix, respectively), and offset of writing the target letter's last stroke (i.e., letter corresponding to onset of second syllable or suffix, respectively). The participants included in the analyses wrote in cursive script, so both the connecting stroke at the beginning of the relevant onset (i.e., between "l" and "f" or between "f" and "e", respectively, in "Gol.f_er"), which is analogous to the inter-letter interval in printed script, as well as the duration of the remaining onset (i.e., "f" or "e", respectively, in "Gol.f_er"), were included in the Letter Duration measure. Writing Onset Duration and Letter Duration were logarithmically transformed to normalize their distributions (Baayen, 2008); however, back-transformed values are reported throughout the article. For each measure, all data points with residuals exceeding three *SD*s from the subjects' and the items' means were excluded (Writing Onset Duration: 1.0%; Letter Duration: 1.4%).

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 morphemic and syllabic processing on Writing Onset Duration and Letter Duration included Writing Onset Duration and Letter Duration, respectively, as the dependent variable in the LMM, and the effect-coded categorical variable of Visual Disruption (3 levels: No vs. Morpheme-congruent vs. Syllable-congruent) as fixed effect. The LMM of Letter Duration additionally included the effect-coded categorical variable of Letter Position (2 levels: Syllable onset vs. Suffix onset) as fixed effect. Participants and items were included as random effects. The LMM of Letter Duration additionally included random slopes for

Table 1 Back-transformed estimated Letter Duration (ms) at the onset of the second syllable (e.g., "f" in "Golfer") and the suffix (e.g., "e" in "Golfer"), respectively, per Visual Disruption

Visual disruption	Syllable			Suffix		
	M (SE)	95% CI	n	M (SE)	95% CI	n
No	1,204 (52)	[1,104, 1,313]	1,210	703 (46)	[615, 804]	1,206
Morpheme-congruent	1,196 (52)	[1,097, 1,304]	1,222	704 (47)	[616, 805]	1,221
Syllable-congruent	1,227 (53)	[1,126, 1,338]	1,221	689 (45)	[602, 788]	1,225

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

both participants and items for the effect of Letter Position, because the shapes of the letters differed between syllable and suffix onsets. The significance of the fixed effects was determined with effect coding and type-II Wald tests using the analysis of variance (ANOVA) function provided in the *car* package (Version 3.0–6; Fox & Weisberg, 2011). Interactions were further decomposed using cell-means coding and post-hoc comparisons using the *glht* function in the *multcomp* package (Version 1.4–12; Hothorn et al., 2016).

Results

Letter Duration

The results on Letter Duration are shown in Table 1. A linear mixed-effects model indicated a significant main effect of Letter Position, $\chi^2(1) = 60.09$, $p < .001$, so that the onset of the second syllable was produced slower than the onset of the suffix, $\Delta = 510$ ms, $t = 7.75$, $p < .001$. There was no effect of Visual Disruption, $\chi^2(2) = 0.16$, $p = .922$. Importantly, Visual Disruption interacted with Letter Position, $\chi^2(2) = 12.31$, $p = .002$. Post-hoc analyses were further conducted to investigate Letter Duration differences between the three conditions for each onset.

At the onset of the second syllable (e.g., "f" in "Gol.fer"), letter durations in the syllable-congruent visual disruption condition were significantly longer than in the morpheme-congruent visual disruption condition, $\Delta = 32$ ms, $t = 2.54$, $p = .011$. The difference between the syllable-congruent visual disruption condition and the no disruption condition was marginally significant, $\Delta = 23$ ms, $t = 1.85$, $p = .065$, and there was no significant difference between the morpheme-congruent visual disruption condition and the no disruption condition, $\Delta = -9$ ms, $t = -0.68$, $p = .495$.

At the onset of the suffix (e.g., "e" in "Golf_er"), letter durations in the syllable-congruent visual disruption condition were significantly shorter than in the morpheme-congruent visual disruption condition, $\Delta = -15$ ms, $t = -2.11$, $p = .035$. Letter durations in the syllable-congruent visual disruption condition were significantly shorter than in the no disruption condition, $\Delta = -14$ ms, $t = -1.97$, $p = .049$, while there was no significant difference between the morpheme-congruent visual disruption condition and the no disruption condition, $\Delta = 1$ ms, $t = 0.14$, $p = .891$.

Table 2 Back-transformed estimated Writing Onset Duration (ms) per Visual Disruption

Visual disruption	*M (SE)*	95% CI	*n*
No	2,780 (92)	[2,604, 2,969]	1,209
Morpheme-congruent	2,879 (95)	[2,696, 3,075]	1,231
Syllable-congruent	2,819 (93)	[2,640, 3,011]	1,230

M = mean. *SE* = standard error. CI = confidence interval. *n* = number of observations

In sum, items with a syllable-congruent visual disruption caused some delay in trajectory formation at the onset of the second syllable (i.e., "-fer"), yet yielded a speedup at the onset of the suffix (i.e., "-er"), relative to the other two conditions, which did not differ from each other. Thus, compared to no disruption, syllable-congruent, but not morpheme-congruent visual disruption had an effect on late measures of handwriting production (i.e., Letter Duration at the two onsets).

Writing Onset Duration

The results on Writing Onset Duration are shown in Table 2. A linear mixed-effects model indicated a significant main effect of Visual Disruption, $\chi^2(2) = 9.63$, $p = .008$. Post-hoc comparisons showed that items in the morpheme-congruent visual disruption condition were initiated slower than items in the syllable-congruent visual disruption condition. However, this contrast was only marginally significant, $\Delta = 60$ ms, $t = 1.86$, $p = .063$. Writing onset durations in the morpheme-congruent visual disruption condition were significantly slower than in the no disruption condition, $\Delta = 99$ ms, $t = 3.08$, $p = .002$, while items in the syllable-congruent visual disruption condition did not significantly differ from the no disruption condition, $\Delta = 39$ ms, $t = 1.23$, $p = .218$.

Thus, items with a morpheme-congruent visual disruption delayed word-writing onset, relative to the other two conditions, which did not differ from each other. Further, compared to no disruption, morpheme-congruent, but not syllable-congruent visual disruption had an effect on an early measure of handwriting production (i.e., Writing Onset Duration).

Discussion

In the present study, we sought to investigate whether morphological effects on handwriting production may manifest in the same way as syllabic effects do (e.g., Hess et al., 2019; Kandel et al., 2011). Morphemes are thought to play an important role in the German language (e.g., Eisenberg, 2013), while German third- and fourth-graders likely have some degree of morphological knowledge (Landesinstitut für Schule und Medien Berlin-Brandenburg, 2015). Therefore, we hypothesized that German children in the third and fourth Grade might make use of morphemes during handwriting, at least when they are explicitly pointed to the morphological structure of printed words. However, it is also likely that German children show a preference for using the sublexical route during writing (Scheerer-Neumann, 2018), as per the

dual-route theory of writing production (e.g., Bonin et al., 2015), via which syllables are thought to be activated (e.g., Miceli & Costa, 2014).

Using a copy task, we asked children to write words that were presented with a morpheme-congruent visual disruption (e.g., "Golf**er**"), and words that were presented without visual disruption (e.g., "Golfer"), as well as words that were shown with a syllable-congruent visual disruption (e.g., "Gol**fer**"). We hypothesized that the use of a morpheme-congruent visual disruption condition would facilitate the activation of the corresponding morphemes via the lexical route, while the use of a syllable-congruent visual disruption would facilitate the activation of the corresponding syllables via the sublexical route. Hence, handwriting behavior should differ between these two conditions. As far as items without visual disruption are concerned, we hypothesized that children are more likely to use the sublexical route. Thus, we expected to observe similar writing behavior in the baseline and syllable-congruent visual disruption conditions, but different writing behavior in the baseline and morpheme-congruent visual disruption conditions.

Our results showed an effect of visual disruption on a late measure (i.e., Letter Duration) in the syllable-congruent visual disruption condition, and on an early measure of handwriting production (i.e., Writing Onset Duration) in the morpheme-congruent visual disruption condition. As such, our findings indicate that visual disruption effects are not limited to the time prior to word-writing onset, but they can also affect trajectory formation. In particular, words with a syllable-congruent visual disruption ("Gol**fer**") produced a delay in trajectory formation at the onset of the second syllable (i.e., "-fer") and a speedup at the onset of the suffix (i.e., "-er"), compared to the other two conditions, which, in contrast to our expectations, behaved similarly. Furthermore, words with a morpheme-congruent visual disruption (i.e., "Golf**er**") yielded a delay in word-writing onset compared to the other two conditions, which, in line with our expectations, behaved similarly.

As far as late measures of handwriting production are concerned, the inhibitory and facilitatory effects observed at syllable and morpheme boundaries in terms of Letter Duration are consistent with previous results reported in the literature (see, e.g., Hess et al., 2019; Kandel et al., 2011, for syllabic effects; and Kandel et al., 2008; Quémart & Lambert, 2019, for morphological effects). The results from these studies show that activation of syllables or morphemes, respectively, in parallel to motor execution, delays trajectory formation at the corresponding linguistic boundaries compared to a control condition. It is worth pointing out that results on syllabic and morphological effects on early measures of handwriting production, such as Writing Onset Duration, are rather inconsistent in the literature (see, e.g., Hess et al., 2019; Sausset et al., 2012, for syllabic effects; and Kandel et al., 2008; Quémart & Lambert, 2019, for morphological effects). The inhibitory morphological effects observed on Writing Onset Duration are consistent with findings from two studies on morphological processing in young adults (Afonso & Álvarez, 2019; Kandel et al., 2008; see also Häikiö et al., 2011, for inhibitory effects of a morpheme-congruent visual disruption on reading). These findings suggest that writers may activate more than one morpheme prior to word-writing onset (see, e.g., Quémart & Lambert, 2019, for activation of one morpheme).

The increased Letter Duration at the onset of the second syllable (e.g., "f" in "Gol.fer") in the syllable-congruent visual disruption condition compared to the other two conditions could be accounted for by the dual-route theory of handwriting production (e.g., Bonin et al., 2015). Syllables are thought to be activated via the sublexical route (e.g., Hess et al., 2019; Miceli & Costa, 2014). Syllable activation is thought to cascade all the way down to delay motor production at the syllabic boundary (e.g., Kandel et al., 2006b). In line with this, we observed increased Letter Duration at the onset of the second syllable. The decreased Letter Duration at the onset of the suffix (e.g., "e" in "Golf_er") in the syllable-congruent visual disruption condition is a consequence of the increased duration of the preceding letter (see, e.g., Kandel et al., 2011, and van Galen, 1991, for similar observations). Our results suggest, thus, that syllabic processing was at play in this condition.

Letter Duration at the onset of the suffix (e.g., "e" in "Golf_er") was shorter in the syllable-congruent visual disruption condition than in the morpheme-congruent and no visual disruption conditions. This result suggests that it takes children significantly more time to produce this letter in the latter conditions. Following van Galen's (1991) idea of parallel processing, we take longer Letter Duration values to suggest that additional cognitive processes must be at play at the suffix onset in the morpheme-congruent and no visual disruption conditions, which could be due to morphological processing. In other words, children might be sensitive to the morphological structure of morphologically complex words, when morphemes are salient (as in the morpheme-congruent visual disruption condition) or not masked by highlighting other relevant units (i.e., syllables).

The second main finding of our study is that Writing Onset Duration was longer in the morpheme-congruent visual disruption condition than in the baseline condition. According to Quémart and Lambert (2019), the orthographic lexicon is organized around morphemes, with writers activating morphological constituents first, and then syllables and letters. Morphological constituents are also thought to be accessed in a serial order (Kandel et al., 2008). One possibility then, in the case of suffixed words, such as "Golfer", is that writers would access the stem "Golf" first, and then the suffix "er", prior to word-writing onset. As the number of morphological constituents prior to word-writing onset increase, Writing Onset Duration should increase too (see Afonso & Álvarez, 2019, for converging empirical evidence). Another possibility, however, is that writers might activate only the initial morphological constituent (i.e., the stem in the case of suffixed words) prior to word-writing onset (Quémart & Lambert, 2019), in which case Writing Onset Duration in bimorphemic words should be shorter than in monomorphemic control words (see Breadmore & Deacon, 2019; Suárez-Coalla et al., 2017, for converging empirical evidence). Both accounts assume that activation of morphological constituents is likely not completed prior to onset of word writing, but cascades all the way down to delay production at morpheme boundaries (Kandel et al., 2008; Quémart & Lambert, 2019; see also Kandel et al., 2012, for converging empirical evidence), even when morphemes have already been activated prior to word-writing onset (Afonso & Álvarez, 2019). In our data, the observed difference between items of the no and the morpheme-congruent visual disruption condition could indicate that participants activate only the stem in the former condition, but the stem and the

suffix in the latter condition (given that the visual disruption makes morphological constituents salient to writers). As a result, Writing Onset Duration is increased in the morpheme-congruent visual disruption condition compared to the no disruption condition. Furthermore, longer Letter Duration at the suffix onset in both conditions relative to the syllable-congruent visual disruption condition suggests that suffix processing must have taken place at this location in the former two conditions, but not in the syllable-congruent visual disruption condition.

An alternative interpretation of our results could be that writers process only syllables and not morphological units.[6] According to this idea, the morpheme-congruent visual disruption condition would inhibit word-writing onset compared to the no disruption condition, because the visual disruption is inconsistent with the word's syllabic segmentation. This would render the visual perception of the word more difficult in the morpheme-congruent compared to the no visual disruption condition, which may explain the differences in Writing Onset Duration between the two conditions. Once children recognized the word, however, the writing process would proceed similarly in both conditions, as evidenced by similar Letter Duration values. In the syllable-congruent visual disruption condition, on the other hand, Writing Onset Duration was not found to be prolonged compared to the no disruption condition, because the highlighting of the syllable was consistent with the word's syllabic segmentation, thus inducing a syllable-by-syllable strategy. This account implies that the decrease in Letter Duration at the suffix onset (e.g., "e" in "Golf_er") in the syllable-congruent visual disruption condition would be a by-product of the corresponding increase at the preceding letter position, i.e., the syllable onset (e.g., "f" in "Gol.fer"). It is worth noting, however, that handwriting production is typically assumed to be anticipatory (e.g., Kandel et al., 2011; van Galen, 1991), which means that writers tend to activate processing units, such as syllables, at their onset or even further ahead. It would be thus surprising, that a syllable-based processing strategy manifests only after the onset of the syllable in the morpheme-congruent and no visual disruption conditions. Further studies are needed to investigate the exact mechanism underlying the observed effect.

The present study extended the use of the visual disruption paradigm from the reading domain (e.g., Hasenäcker & Schroeder, 2017) to the writing domain. This is interesting not only from a cognitive, but also from an educational perspective, because according to recent approaches of formal literacy instruction, beginning readers and writers might benefit from visual disruptions highlighted in text; hence, this technique could be potentially used in textbooks (see, e.g., Donth-Schäffer et al., 2013; Kuhn & Mrowka-Nienstedt, 2016, for textbooks). Our findings suggest that the visual disruption paradigm could be used to point children to the morphological or syllabic units in printed words. Importantly, German third- and fourth-graders seem to be sensitive to the morphological structure of morphologically complex words: pointing them explicitly to it inhibits onset of word writing (see also Häikiö et al., 2016, for inhibitory effects of visual disruptions on word recognition speed). It is also worth noting that children in Germany are typically taught

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[6] We thank an anonymous reviewer for suggesting this alternative interpretation.

phoneme-to-grapheme correspondences first (see, e.g., Landerl & Thaler, 2013, for an overview). Recent educational approaches tend to focus, however, on syllables and morphemes from the beginning of formal literacy instruction (e.g., Röber, 2009). Further research would be needed to compare how drawing the focus on linguistic units such as syllables or morphemes from the beginning of formal literacy instruction could potentially affect handwriting speed and spelling accuracy. Real-time data are critical for achieving this (Hess et al., 2020).

In conclusion, our study used a set of tightly controlled experimental stimuli to investigate effects of morphological processing on handwriting production in the German language. Our work contributes to the empirical evidence in handwriting research, tentatively suggesting that morphemes, in addition to syllables, are functional units in developmental handwriting. Further developmental research with children from different grades and in different languages is needed to track the point in time at which morphemes might start to be processed during writing development, and to determine the factors that influence morphological planning prior to word-writing onset. An additional challenge in future research is to determine whether making linguistic units such as syllables or morphemes salient from the beginning of literacy instruction could improve writing skills.

Appendix

See Table 3.

Table 3 Materials

	Visual disruption	
No	Morpheme-congruent	Syllable-congruent
Sünder	Sün**der**	Sün**de**r
Zünder	Zün**der**	Zün**de**r
Finder	Fin**der**	Fin**de**r
Lenker	Len**ker**	Len**ke**r
Henker	Hen**ker**	Hen**ke**r
Denker	Den**ker**	Den**ke**r
Heiler	Hei**ler**	Hei**le**r
Reiter	Rei**ter**	Rei**te**r
Neider	Nei**der**	Nei**de**r
Glaser	Gla**ser**	Gla**se**r
Planer	Pla**ner**	Pla**ne**r
Kleber	Kle**ber**	Kle**be**r
Hefter	Hef**ter**	Hef**te**r
Golfer	Gol**fer**	Gol**fe**r
Laster	Las**ter**	Las**te**r
Halter	Hal**ter**	Hal**te**r
Sender	Sen**der**	Sen**de**r
Helfer	Hel**fer**	Hel**fe**r
Festung	Fest**ung**	Fes**tu**ng
Landung	Land**ung**	Lan**du**ng
Rundung	Rund**ung**	Run**du**ng
Rüstung	Rüst**ung**	Rüs**tu**ng
Färbung	Färb**ung**	Fär**bu**ng
Lüftung	Lüft**ung**	Lüf**tu**ng
Teilung	Teil**ung**	Tei**lu**ng
Leitung	Leit**ung**	Lei**tu**ng
Zeitung	Zeit**ung**	Zei**tu**ng
Warnung	Warn**ung**	War**nu**ng
Haftung	Haft**ung**	Haf**tu**ng
Meldung	Meld**ung**	Mel**du**ng
Bergung	Berg**ung**	Ber**gu**ng
Werbung	Werb**ung**	Wer**bu**ng
Tarnung	Tarn**ung**	Tar**nu**ng
Neigung	Neig**ung**	Nei**gu**ng
Reibung	Reib**ung**	Rei**bu**ng
Heizung	Heiz**ung**	Hei**zu**ng

Bold type appeared in (non-bold) orange font color in the printed stimulus words

Declarations

Conflict of interest The author declared that there is no conflict of interest.

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