Chapter XX
Morphemes, syllables and graphemes in written word production

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1. Introduction

Until recently written language and writing have been considered to be of minor interest in the context of cognitive and linguistic theories. Though the practical relevance of writing competences is undisputed, research in language production was, initially, research into speech production. This limitation was mainly due to the widespread opinion that spoken language is the exclusive domain of linguistics because of its 'naturalness', whereas written language was considered to be 'invented'. As a consequence, it was held to be more of a technical problem, e.g. in teaching, language policy or typography. This idea can be traced back to Saussurean linguistics: "Only the spoken word is the objective of linguistics." (Saussure 1967[2]: 28; our translation).

For several reasons the situation has completely changed over the last few years. Research in the history of writing systems has demonstrated that it is not just a matter of intentional acts of script reforms but of autonomous system developments. This idea goes as far as analysing aspects of writing systems in the framework of the Optimality Theory (Primus 2003). At the same time, there is converging evidence that the individual development of reading and writing competence is not simply a direct result of school teaching, but of the learners' reconstruction of the orthographic rule system (e.g. the "self-teaching hypothesis", Share 1999). Accordingly, one major question for future linguistic research will be to find out, whether written language and its historical and individual developments have to be treated in the same theoretical frameworks – e.g. Universal Grammar, Optimality Theory or Learnability Theory - as other types of linguistic systems (like spoken language or even sign language).

In this paper we will summarize our research on written word production and discuss it in the context of other empirical results and models of written language production. Due to methodological reasons, the studies reported focus on typing instead of hand writing or oral spelling. As we are not interested specifically in motor processes but in cognitive and linguistic processes in writing, we chose typing as the most advantageous mode. Certainly, typing is a (discontinuous) motor task and the time course of typing is to a certain amount determined by motor conditions. But the methodology presented below allows for a differentiation between various factors determining the time course. Hand writing, on the other hand, is a continuous and much more complex motor task and hence it is much more difficult to separate linguistic and non-linguistic factors. Finally, oral spelling is on the one hand not determined by graphomotor processes (instead, articulomotorics) but on the other hand it is very slow and certainly not the main mode of writing.

In the following section we give an overview on studies about time structures in typing and summarize methodological implications of typing for experimental research. Finally, we will discuss our own approach. The third section is devoted to the influences morphological word structure exerts on word writing. In the fourth section we present results on syllables as processing units in writing. A special emphasis is given here to the question, whether or not syllabic structures in word writing are determined by phonological processes. In the fifth section studies on graphemes are

reported, which are, from a linguistic point of view, the basic functional units in the structure of written language. It is suggested that they are also processing units in the cognitive system. The sixth section summarizes the studies reported and suggests a model of word writing that in major respects differs from models proposed by other authors. In the final section questions still open and ideas for future research are presented.

2. Investigating the time course of typing

2.1. Linguistic processes and the time course of typing

The early 1980s saw a surge of studies on typing as skilled motor behavior that have essentially informed our present understanding of the organization of motor processes involved. However, relatively little has emerged from these studies to enhance our understanding of central cognitive processes underlying language production, and there appear to be two main reasons for this. On the one hand there it is widely held that written language production is entirely, or for a large part, dependent on spoken language – a view apparently supported by studies on normal language performance as well as by clinical-neurological studies (e.g. Frith, 1979, Geschwind 1974, Luria, 1966, Wernicke, 1886. For a review see Ellis, 1982). On the other hand, studies concerning writing as a skilled motor behavior, especially typewriting, have promoted the view that the motor system involved is to a large extent, if not completely, independent of higher cognitive language processes. As a consequence, timing and time structures in writing were thought to contain little, if any, information allowing for an analysis of processes involved in written language production. Research approaches in this domain are marked by the fundamental assumption that input into the motor system is constituted by a completely specified set of lexical-orthographic information. Hence, time structures in typewriting have been studied almost exclusively with respect to organization of motor processes, control structures in highly skilled performances, and representations of skilled motor acts, all of which appear to be reflected in both the latency of initiating typing movements and the timing of the actual responses (e.g. Cooper, 1983; Ostry, 1980, 1983; Shaffer, 1978; Sternberg et al. 1978).

Although several writers have hinted at the influence of syllables on writing and the time course of writing (Ellis, 1982; Marcel, 1980; Ostry, 1983; Shaffer, 1978; Wing, 1980; Terzuolo and Viviani, 1980; Gentner, Larochelle and Grudin, 1988), none of these studies have promoted the view of syllables as processing units in typing. Van Galen (1990) claims to have identified a syllabic influence in handwriting: syllable repetition seems to shorten initial latency and lengthen writing time of words. However, his results are also explainable as effects of polygrapheme repetitions and may have nothing to do with syllables as central processing units. Such an interpretation is supported by the study of Zesiger et al. (1994) who were unable to demonstrate an influence of syllable structure on either reaction time or production time in handwriting. However, the authors found increased interkey intervals for within-word syllable boundaries in typewriting. In addition, a semantic word effect – words are written faster than pseudo-words – , a word frequency effect – high frequency words are typed faster than low frequency words – , and an influence of word units (Gentner, 1983; Zesiger et al. 1993; Terzuolo and Viviani, 1980) have been reported by previous studies. Terzuolo and Viviani (1980) postulate permanently available motor engrams for words because they found words were written with constant timing patterns and there were different timing profiles for different words. However, the studies mentioned did not control for all factors affecting keystroke timing, and the question of what constitutes processing units in writing/typing still is a matter of debate.

In a series of recent studies (hier koennen wir alle Arbeiten des Projects anfuehren) that we are going to review here, we have put forward ample evidence that the time course of motor activities in writing/typing is not independent of the linguistic processes of written language production. Therefore the analysis of the time structure of writing, handwriting as well as typewriting, might offer an interesting approach to the analysis of the processing architecture in written language production, at least in as far as the processes involved are manifesting themselves in the time domain.

2.2. Methodological considerations

The long span of writing/typing research and the ensuing controversies with respect to influences of linguistic factors on writing/typing would definitely merit an in-depth reconsideration of methodological approaches applied in this research. Although the present volume does not allow us to do that, we would at least like to take the opportunity to detail to some extent the rational behind the approach that was developed by our group, an approach, we believe, that has effected a series of promising studies. The development of that approach was guided by the interest in identifying linguistic factors that might influence the time structure of writing and typing, and for that purpose, as the history of writing research teaches us, it is obviously important to identify and try to isolate as many as possible of the non-linguistic factors that influence this timing.

Our research is based on the analysis of discontinuous typing (single word typing), an approach, pioneered by Sternberg et al. (1978) and Ostry (1980), in which subjects are requested to type a single word (delayed or non-delayed), following the presentation of a signal, for instance a visually or acoustically presented word or a picture whose name is to be typed. This type of experiment gives two essentially different types of time information, initial latencies and series of interkey intervals. Initial latencies (ILs) are the time intervals between the presentation of the word stimuli (or, in the delayed conditions, a separate start signal) and the first keystroke and contain information related to processes operand during this time span. Interkey intervals (IKIs) are the time intervals between successive keystrokes and contain information about processes active between keystrokes.

It has already been reported (Shaffer, 1973; Gentner, 1983) that interkey intervals in typing experiments show markedly right skewed, non-normal distributions (see Fig.1). Therefore, an adequate way of treating these data would have been to describe them in terms of median and interquartile range and analyze them with non-parametric statistical procedures.
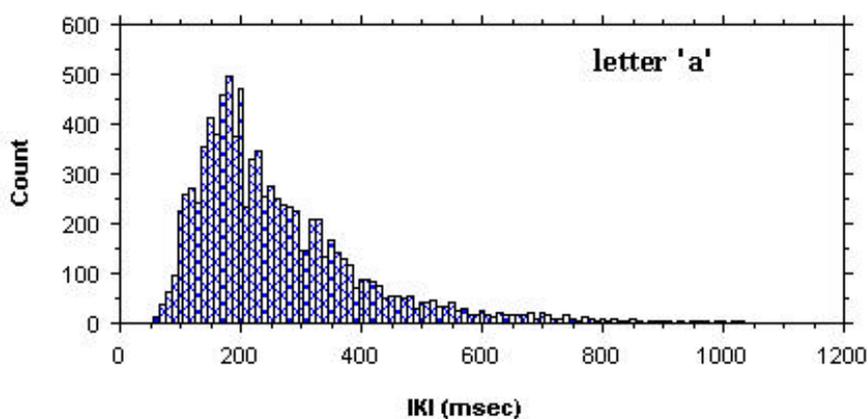

Fig.1: skewed IKI distribution for letter 'a' in German typing experiments (n=9427, typed by 136 subjects).

However, for two reasons we abstained from such an approach. First, in the studies referred to here, we were not concerned with analyzing data from individual typists, but with revealing general tendencies in relation to certain speed groups (fast and slow typists). For that purpose we averaged the original measurements over subjects within each of the speed groups. The latter were formed,

following determination of individual typing speeds, in such a way that each group contains roughly the same number of typists. The averaging procedure gives us mean values which in turn can be presented by means (of means) and analyzed by parametric procedures, as means of means can be assumed to follow a normal distribution. Secondly, most studies on typewriting (e.g. Cooper, 1983; Ostry 1980, 1983; Larochelle, 1983) use means and parametric statistics to describe and analyze their data. If we were to describe our analyses in terms of non-parametric statistics, results would be difficult to compare with those studies. Our approach also seemed justified in the light of Gentner's (1983) report that he did not find significantly different results when describing the distribution of his IKI data in terms of SD rather than in terms of interquartile range.

Keystroke timing in typewriting has been shown to be dependent on a set of various factors (e.g. Gentner, 1983; Larochelle, 1983; Ostry, 1980, 1983; Shaffer, 1978; Sternberg et al. 1978), the most important being typing speed, layout of typewriter keyboard, and physical constraints of hand movements. The timing of a keystroke within a stroke sequence is also influenced by whether the preceding stroke is executed by a different or same hand (see fig.2), and, in the latter case, it makes a difference whether it is typed by the same or a different finger. These influences on the interkey time are affected by typing skills (Gentner, 1983; Larochelle, 1983).
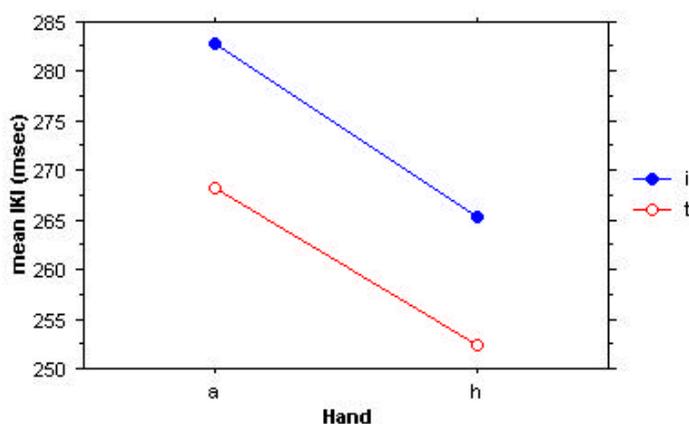

Fig.2: *Mean IKIs for intra-syllabic letters 'i' (n=305) and 't' (n=292), split according to whether the preceding letter is typed with a finger of the other (a) or the same (h) hand.*

Other factors influencing keystroke timing are related to statistical language features (word and letter frequency) and typing context. The word frequency effect, i.e. the fact that frequent words are typed faster than infrequent ones – first described over sixty years ago (Fendrick 1937) – is taken as indication for the involvement of lexical processes in word recognition and production (Shaffer 1973). Gentner, Larochelle, and Grudin (1988) explored the effect in a controlled experimental design: They compared word pairs sharing an identical four-letter sequence which were either high or low in frequency and found that the word frequency effect, although small (10 ms), was significant. The results were not affected by word length and syllable boundaries and the typing rate increased over repetitions for low frequency words only.

Letter frequency is another important factor affecting IKI durations. If we take a look at the mean IKIs for letters as they emerge from a series of typing experiments (Fig. 3A) we find a considerable range of different durations, with the 'slowest' IKIs about three times longer than the 'fastest'. A large part of this variance is explained if we examine the correlation between IKIs and logarithms of letter frequencies (Fig. 3B). Obviously, letter frequency exerts an influence on keystroke timing in a way that higher frequency letters are typed with shorter IKIs.
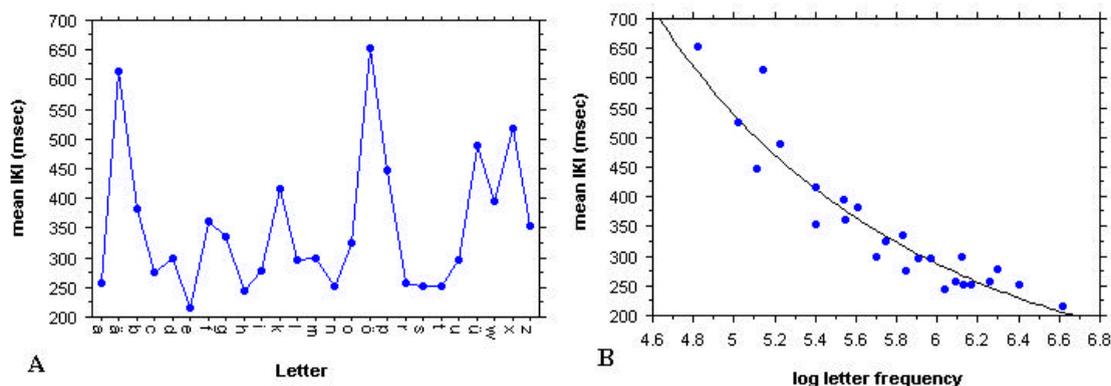
Fig.3: *(A) mean IKIs for within-word letters (n= 79 004) from 10 typing experiments in German and (B) regression plot for log letter frequency and mean letter IKI.*

Despite indications that single keystrokes are the basic units of motor performance in typing (Rumelhart and Norman, 1982; Larochelle, 1983), Shaffer (1978) and Gentner (1983) have demonstrated a 'context' effect on keystroke timing by up to 3 preceding and 1 succeeding character, with the effect appearing to transcend even word boundaries. According to Gentner (1983) the strongest influence is exerted by the immediately preceding character, which seem to reduce the variability of IKIs (in terms of interquartile range) by about 43%. This conforms to the findings of Larochelle (1983), that tri-graphs and higher level n-graphs seem to contribute very little to the timing of keystrokes. Probably related to this context effect is the way in which polygraph frequencies influence IKI durations in the polygraph. For example, in our German data durations of initial digraph IKIs (i.e. timing of the first key stroke in a digraph) correlates significantly with inverse logarithm of the digraph frequencies. That is, if we take all digraphs commencing with letter 'a' then the IKI size for the 'a's is influenced by the frequency of the respective digraphs. However, if we take all digraphs in which the second letter is 'a', then there is no correlation between IKI size (for this character) and digraph frequency.

2.3. Our approach

The interest in the influence of linguistic units on writing/typing boils down to the question of whether units like morphemes, syllables, and graphemes are operant units in the production process that are reflected in the time structure of writing/typing. In order to answer this question through analysis of our chronometric data, we have defined a variable 'type of boundary' that identifies the type of linguistic unit commencing at certain points in a word. It classifies interkey intervals (IKIs) according to the type of linguistic boundary at which they occur: 'SM' denotes IKIs at combined syllable and morpheme boundaries; 'S' represents IKIs for characters at the onset of syllables alone, whilst 'M' signifies those at 'pure' morpheme onsets. L specifies IKIs for characters at all other positions within a word, i.e. at all within syllable or within morpheme positions. For example, in the English word 'c-o-n-f-o-u-n-d-e-d' the following IKI-types would be identified: SM-IKI between 'n-f', S-IKI between 'n-d', M-IKI between 'd-e', all other IKIs being of type L.

With the knowledge about the various factors influencing IKI durations it is obvious that if we were to perform a simple 'type of boundary' analysis of our data on the basis of all letter IKIs, we would be confronted with multiple confounds. For example, if letters at syllable boundaries had longer IKIs than at within-syllable positions, this could be due to the fact that letters at syllable boundaries have lower frequencies than the within-syllable letters. Even if we take care to compare only the identical letters for the two IKI types, the same result could have been produced by a 'con-

text' effect: the letters might be surrounded by different letters in the two 'contexts'. In addition there could be a 'handedness' effect: the preceding letter could have been typed by the same hand in one condition, but by the other hand in the second condition. Obviously, this is not the way to go.

Instead, one has 1) to compare only identical letters under all conditions of the main factor (type of boundary) and 2) to keep the context fixed for the various conditions.

In order to comply with the second point, we have to compare at least digraphs. According to Gentner (1983) this would reduce context variability by about 43%. Furthermore, as the 'letter of interest' is the same under all conditions, letter frequency is controlled for. The same holds for digraph frequency, as the 'letter of interest' is the second one in the digraph (see above). Analysis on the basis of digraphs also seems to solve the problem that interkey intervals are affected by whether a character sequence is typed by finger strokes of one hand or by alternating hands (see Fig. 2) and the way this influence is dependent on typing skill (Gentner, 1983; Larochelle, 1983). However, as participants in our experiments showed a large range of typing skills in terms of typing speed, we had no way of telling how digraphs actually had been typed by a certain participant, as we did not require them to have learned typing according to a standard method (although all participants were able to type fluently without obvious hesitation). We can, nevertheless, assume that for each subject all occurrences of a specific digraph are generally typed in the same way. An analysis on the basis of digraphs, then, takes into account the various motor performances without requiring us to know how the keystroke sequences were actually executed.

Although such a procedure still leaves some context variance unaccounted for, it is not feasible to extent the fixed context to three letters, as there would be hardly sufficient word material available for the comparison. We are, therefore, going to analyze the 'type of boundary' influence on IKI size on the basis of digraph sets. However, language specific constraints prevents us from working with a single digraph set for the for conditions (SM, S, M, and L type IKIs), we simply could not assemble wordlists with sufficient number of cases[1]. In order to overcome the language constraints and to obtain substantial word lists, we decided to use three different sets, each with digraphs occurring at one of the boundary types (SM, S, M) as well as at within-syllable positions (L). Again due to language constraints, these digraph sets do not contain all existing digraphs for each condition, but only a limited number of digraphs that occur under at least two conditions. All of these sets, however, were controlled for a balanced number of occurrences under the two conditions for each set.

3. Morphemes

Orliaguet and Boë (1993) postulate morphemes as being the processing units of typing. They found prolonged latencies and writing times[2] in a production task in which participants applied grammatical rules on the to-be-written words. The finding that solving an orthographic ambiguity through the application of a grammatical/morphological rule (pluralization or conjugation) is an additive process that produces timing delays provides evidence that the morpheme is a suprasegmental processing unit under these conditions. Results pointing in the same direction were obtained by Pynte, Courrieu, and Frenck (1991) in a handwriting experiment. However, all of their morpheme boundaries were also syllable boundaries an obvious confound not considered in their conclusion that morphemes are the only processing units of writing.

Postulating morphemes as processing units needs to take into account the different types of morphemes that might affect, in different ways, processes involved in word writing. In German, three main types of morphemes can be distinguished: stem morphemes, derivational morphemes and inflectional morphemes. Whenever a stem morpheme begins *within* a word a syllable always begins simultaneously. The same is true for within word prefixes (derivational or inflectional, e.g. in prefix+prefix+stem constructions) and for suffixes with a consonant onset. Vowel onset suffixes are re-syllabified (Ach-t#ung, Kin-d#er) leading to a mismatch between syllable and morpheme

onset (for a discussion of the differences between phonotactical and graphotactical syllable boundaries see section: Syllables).

In studies on spelling errors of an acquired dysgraphic patient, Badecker, et al. (1990, 1996) found that inflectional word-final forms were preserved but not non-inflectional word-final forms (e.g. the <ed> ending in <surfed> was preserved in the response <sourphed>; responses like <sourpht> were infrequent; on the contrary <ed> endings were rarely applied to phonologically possible candidates like <crypt> as <cripped> but were mostly realized as <cript>). They concluded that, at least in this patient, stem morphemes were produced phonographically but the inflectional form was added through a lexical process (see below).

If *all* types of morphemes serve as a processing unit in writing, interkey intervals for identical digraphs from different words spanning (a) 'pure' morpheme boundaries and (b) no linguistic boundary should differ, i.e. the initiation of the new morpheme should cause a prolonged interkey interval (digraph paradigm, see section: 2.3). Our experiments (Will et al. 2003a, 2003b) revealed no significant differences between 'pure' morpheme boundaries (henceforth: M-type) and 'simple' letter transitions (henceforth: L-type). One might argue that all morphemes beginning at 'pure' morpheme boundaries begin with a vowel and that these are typed faster than consonants (especially in the case of the very frequent <e>). This possible explanation is precluded by the digraph paradigm with identical digraphs in the test and control items. Another point is the position of the digraph within the syllable: most 'pure' morpheme onsets are situated at the second character position within syllables – a position known to have a timing advantage (Ostry 1983). Even when these effects are controlled, no significant differences between M-type boundaries and L-type transitions occur (for a more detailed discussion see Will et al. 2003a). If one takes for granted that morphological units are, to a certain degree, independently accessible (at least for inflection, see Badecker et al. 1990, 1996) and that they can be independent information units retrieved from the lexicon, we must conclude that 'pure' morpheme units are not necessarily executed at their onset.

In contrast to 'pure' morpheme boundaries, intervals for digraphs where a morpheme and a syllable boundary coincide (henceforth: SM-type) were prolonged (Will et al. 2003a, 2003b,), i.e. semi-skilled typists (58 words/min.) need on average more than 110 ms longer to type, for example, the digraph <l-s> in words like <Roll-schuh> 'roller-skate' or <Schaukel-stuhl> 'rocking chair' than to type the same digraph in <Hal-stuch> 'neckerchief' or <fal-sch> 'wrong'. Although 'pure' syllable boundaries (henceforth: S-type) were also found to have an effect on interkey intervals, i.e. they give rise to longer interkey intervals than identical L-type digraphs, SM-type and S-type interkey intervals differ significantly. Participants need on average 70 ms less to type, for example, the 's' in S-type digraph <l-s> (in words like <Fel-sen> 'rock') than in the corresponding SM-type digraphs (see section: Syllables). In fact, the coincidence of linguistic boundaries leads to the longest delays in within-word typing. This result, together with the previously mentioned findings (no 'pure' morpheme effect), sheds a different light on the Pynte, Courrieu, and Frenck (1991) conclusions: Morphemes are processing units in writing if their boundaries coincide with a syllable boundary.

These results also give a clear hint for a separation into root morphemes and affixes. This view is supported by the theoretical findings of connections between syllable and morpheme boundaries: In German a root morpheme can contain more than one syllable but a syllable cannot contain more than one root morpheme. An affix rarely contains more than one syllable but a syllable can span more than one affix (mostly suffixes). Empirical evidence for a different representation of stems and affixes comes from clinical studies: Tyler, Behrens, and Cobb (1990) postulated a separate representation of the stems and suffixes of derived and inflected words. Autonomous processes for derivation and inflection were also proposed by Miceli and Caramazza (1988) and additionally for composition by Cholewa and de Bleser (1995).

Although significant differences between M-type boundaries (all from suffixes) and L-type transitions could not be found, we compared the effects of different morpheme types on the SM-type interkey intervals in a post hoc analysis (Nottbusch, Weingarten, and Will 1998). The intervals

were longer when the digraph spanned the boundary between two stem morphemes (e.g. <n-e> in <Korn-ernte> 'corn harvest') than between two derivational morphemes (e.g. in <an-erkennen> 'acknowledge'). Similar results were found by the authors when number and duration of pen lift-offs in handwriting were analyzed.

These results were replicated in a recent study on typing with an increased number of words and controlled digraphs (Nottbusch, Grimm, and Weingarten 2003b). The SM-type interkey intervals were split into the following sub-types:

(1) prefix+prefix+stem constructions, i.e. a new *prefix* starts with the second character of the digraph (as for <r-z> in <vor-zer#kleinern> 'pre-reduce to small pieces'),

(2) stem+stem constructions, i.e. a new *root* morpheme starts with the second character of the digraph (e.g. <Roh<u>r-z</u>ange> 'pipe-wrench'), in order to control for effects of the preceding morpheme we also used (2b) prefix+stem constructions as a control type (e.g. <ze<u>r-z</u>ausen> 'tousle'), and

(3) stem+suffix constructions, i.e. a new *suffix* starts with the second character of the digraph (e.g. <Tapfe<u>r-k</u>eit>[3] 'bravery').

Furthermore, derived stimuli consisted exclusively of productive paradigms and the root was relatively more frequent than the whole word for all items. In addition, all items were semantically transparent and unambiguous. Results were as follows: Differences between constructions of type (1) and (2) were negligible (< 7 ms). The control items (2b) were slightly faster (14 ms, but non-significant) than those of type (2). In contrast the stem+suffix forms (3) showed shorter interkey intervals at the SM onset than the stem+stem items. The difference of 55 ms was significant.

In order to discuss these results one has to consider that for prefixes a subsequent unit (including a stem) is obligatory. This is not the case for suffixes. Therefore we assume that the access to prefixes is influenced by frame information of the following unit containing a stem.

(1)   [Prefix]   +   [[Prefix]+[Stem]]
(2)   [Stem]   +   [Stem]

There seems to be a weak but consistent influence of the preceding unit as found in the control items of type (2b).

(2b)   [Prefix]   +   [Stem]

A unit following a suffix is optional (this can - per definition - only be another suffix or a new frame containing a stem.)

(3)   [Stem]   +   Suffix]

In the case of Stem+Suffix constructions the access to the suffix is faster - no further information is needed.

We could not replicate the word frequency effect reported by Gentner, Larochelle, and Grudin (1988) for all types of boundaries although highly frequent words were typed faster in general. In fact, no significant word frequency effects were found at any within-word position, except for interkey intervals for digraphs where a morpheme and a syllable boundary coincide (SM-type). Interkey intervals at SM-type boundaries were significantly faster in high frequency words than in low frequency words (Will et al. 2003b), i.e. for example, the digraph <t-s> is typed significantly faster in highly frequent words, e.g. <Ze<u>it-s</u>chrift> 'journal' than in low frequency words, e.g. <Kra<u>ft-s</u>port> 'weight training'. As, according to Jescheniak and Levelt (1994), the word frequency effect can be taken as evidence for lexical access, our interpretation of these results is as follows: Morphologically complex words are structured (and maybe stored) as subunits of the SM-type. To activate these units lexical (re-)access is necessary. (Post-lexically these units are further processed at the level of syllabic sub-units (see section: 4. Syllables).)

There are two possible ways of access procedures for morphologically complex words: 1. a whole word access procedure or 2. a compositional access procedure. In current models both routes are considered and either thought to compete (e.g. Caramazza, Laudanna, and Romani 1988, Luzzatti, Mondini, and Semenza 1999) or converge onto a single representation (Baayen and Schreuder, 1999). A proposal to predict the (faster) processing route in perception on the basis of *relative*

frequency, was recently made by Hay (2000). According to Hay (2000), morphologically complex words are decomposed if the stem is more frequent than the whole term, otherwise they are retrieved as stored whole words. As the results of Will et al. (2003b) were based on data of whole word frequencies, it can not be excluded that the observed effect originates from base frequencies, because in German compounds the frequency of the second (base) stem is typically higher than that of the whole word. We therefore conducted a further experiment (Nottbusch, Grimm, and Weingarten 2003b) with compounds that were varied in two dimensions: 1. frequency relation between the whole word and that of the base and 2. frequency level (low vs. high) of the relatively more frequent part. The hypothesis was: If complex words are composed in written word production (and are not accessed in a holistic way) the level of the whole-word-frequency should not affect the interkey interval spanning the boundary between the two stems. Instead, the interkey interval should be influenced by the frequency of the base. To give an example: the interkey interval within the digraph <t-g> should be shorter in words like <Sekt-glas> 'champagne glass' than in words like <Mast-gans> 'fattened goose' because the second morpheme in the first example, <Glas> 'glass', is much more frequent than that of the second example, <Gans> 'goose', while the whole-word frequency is low for both compounds. Items were also controlled for semantic transparency.

The hypothesis was not confirmed: Word frequency affects the duration of SM-type interkey intervals independent from the level of base frequency, i.e. corresponding intervals were shorter in highly frequent words than in infrequent words, and this effect was independent of the frequency of the SM-unit starting with the to-be-typed key. This means that interkey intervals of the SM-type (at the boundary of the two components) are affected by the frequency of the whole word but not, or to a far lesser extent, by the frequency of the base. There were no interactions with semantic transparency[4], and although all SM-interkey mean values in semantically intransparent items were faster than those of the semantically transparent items, this effect was not significant. We therefore conclude that we are not dealing with compositional effects but with a re-access of the whole-word form.

As already mentioned, Gentner, Larochelle, and Grudin (1988) assume the perceptual level to be the locus of the word frequency effect. Zesiger et al. (1994) are of the same opinion for any syllable effect. To explore the locus of the above mentioned effects we conducted several experiments containing different presentation modes (written words, spoken words, and pictures) as well as variations in the delays between stimulus onset and typing.

In written picture naming, all the information necessary for writing must be obtained via lexical activation (independent of any phonological or graphemic information derived directly from written or spoken word stimuli). Therefore, if augmented delays at SM-type interkey intervals were to result from information made available by the stimulus, they should not be found in the time course of typing in a written picture naming task. However, the coincidence of a syllable and a morpheme boundary leads to the longest within-word delays in written picture naming, i.e. interkey intervals of the SM-type were significantly longer than those of the S-, M- and L-type in identical digraphs (Will, et al. 2003b). Hence, we conclude that the effect is attributable to the production side.

The direct comparison of the time course of typing following written and spoken word stimuli can be used to test the hypothesis of an obligatory activation of the phonological representation prior to the generation of corresponding graphemic forms, as proposed for example in the van Galen (1991) model of handwriting. In the case of written word stimulus, information on the graphemes and their sequential order is given but it lacks the phonological information delivered by the spoken word stimulus. Therefore, if a phonological mediation would be obligatory the graphemic information delivered through the written word stimulus would have to be converted to phonological information in order to activate the representation in the Graphemic Output Lexicon. Due to this additional process, one would expect prolonged initial latencies and SM-type interkey intervals (under the provision that these reflect lexical access) for written word stimuli compared to spoken word stimuli. Unfortunately, initial latencies for the two different presentation modes cannot be compared in an undelayed task (the written word is presented 'at once', spoken word stimuli have

varying durations and it is impossible to determine the point in time when 'sufficient' information to initiate writing is delivered). Nevertheless, a significant effect of the presentation mode on the duration of SM-type interkey intervals was found (Will, et al., 2003b). However, in contrast to our predictions on the basis of the van Galen model, SM-type interkey intervals were significantly longer (average: 35 ms) in the spoken than in the written word presentation. All other types of within-word interkey intervals were not significantly affected by the presentation mode. This result is in accordance with findings from several clinical studies (e.g. Rapp et al. 1997) that assume an autonomous orthographic pathway. The shorter latencies in the written word condition indicate that the representation in the Orthographic Output Lexicon is activated without an additional process related to phonological recoding. In contrast, the longer latencies in the spoken word condition could be caused by the mediated activation of the graphemic word form via the phonological word-form since the possibility of a sublexical Phoneme-Grapheme-Conversion procedure at the SM-type boundaries is not likely because of the observed lexical-dependant word frequency effect. As SM-type interkey intervals are affected by whole-word frequencies (see above), in a similar fashion to word initial latencies, we hypothesize that – although not measurable in our experiments for techni-cal reasons – initial latencies following spoken word stimuli are also longer than those following written word stimuli.

In an additional experiment, Will et al. (2003b) investigated the influence of preparation time[5] in typing visually (written) and orally (spoken) presented words. The main characteristics of the time course remained unaffected: Words are still typed with augmented SM-type interkey intervals and the delay also had no effect on within-syllable interkey intervals. Interestingly, in contrast to the above mentioned immediate writing condition, typing was different with respect to the influence of presentation mode on SM-type interkey intervals in the delayed writing condition: the additional preparation time 'absorbed' the differences between the two presentation modes. Additionally, there were no significant differences for the initial latencies of both presentation modes. These findings lead us to the following interpretation: In the case of delayed typing factors, features reflecting the stimulus type are no longer detectable in the time structure. This conclusion is in accordance with results from a handwriting study conducted by Bonin et al. (2001:705), where word frequency af-fected initial latencies in immediate but not delayed writing. Interestingly, however, the additional preparation time does not seem to lead to complete specification at segmental (character) level as there is no significant difference in the timing of the remaining interkey interval types if compared with the un-delayed condition. The fact that augmented SM-type interkey intervals are detectable under *all* conditions mentioned above gives strong evidence for the psychological reality of lexical constituents below the word level corresponding to SM-units in written word production.

4. Syllables

In oral language production syllables organize articulatory processes in a way such that, roughly speaking, syllables can be defined as consisting of an opening and a closing movement of the ar-ticulatory organs. These movement phases determine a distribution of segmental sounds across the whole syllable. The more noisy sounds – i.e. consonants – can be found in those phases, where the articulatory organs are still or already closed to a certain degree: at the beginning and at the end. The more sonorous sounds – esp. vowels – can be found in the centre, when the articulatory organs are more opened and do not cause too many disturbances of the air stream. This rhythmic alterna-tion of consonants and vowel, supports the auditory analysis of the hearer. Independent from su-perordinate linguistic structures such as lexical, morphological or syntactic structures, this alterna-tion structure of the speech signal is a basic property of language in general.

In most cases it seems to be quite obvious, how many syllables are contained within a word. For example, the German word [ˈhal.tən] (to hold) consists of two syllables, even if we consider the more common, reduced form [ˈhal.tn̩]. There are two voiced nuclei that are separated by the voice-

less sounds [t]. If the sound sequence is embedded in a sentence, though, intuitively a different segmentation might be appropriate: [ˈhalt.n̩.ˈfɛst] (Halt´ ihn fest!'Keep hold of him!'). Not only syllable boundaries but also the number of syllables of an expression can depend on the assignment of a linguistic structure. For example, the expression [ʔalm] may be considered as consisting of one syllable, if it is interpreted as the German word *Alm* 'alpine pasture'. Otherwise, if it is interpreted as the word *allem* 'all, Dat.' in an everyday pronunciation, it would be said to have two syllables (in IPA-notation: [ʔal.m̩]), though the acoustic characteristics may be exactly the same.

These examples indicate that in some cases syllable boundaries and the number of syllables depend on the assignment of a super-ordinate linguistic structure to an expression. This problem arises especially in languages with a complex syllable onset and coda such as the German language. Accordingly, the way syllables are actually produced is not only a matter of articulation, but has an intricate relation to other aspects of linguistic structure. The aforementioned independence of the syllabic alternation structure holds true only for a rough analysis of the speech signal. In many cases the final syllabic analysis can only be accomplished if other (superimposed) linguistic structures are taken into account.

The interconnections between syllabic and other linguistic structures may be considered as one motivation for the idea that the domain of this basic alternation structure is not restricted to oral language, but presumably is fundamental for every mode of language: oral, written and even sign language.

As far as written language is concerned, in German orthography there is one major difference to oral language. Whereas a syllable in oral language may lack a vocalic nucleus (s. the above cited expression [ʔal.m̩]), every syllable nucleus in written language contains at least one vowel grapheme. This fact indicates the importance of the syllabic structure in written German. The consistent alternation of consonants and vowels makes sense if it supports the reader in analyzing the structure or written expression. It should be noted that this alternation structure is of a rather abstract nature, because, in contrast to the information the speech signal delivers to the listener, visible language contains only sparse support for basic visual perception in syllabic segmentation. Instead, the syllabic alternation structure becomes evident, only after graphemes are categorized as vowels or consonants.

The German writing system is not a syllabic writing system as e.g. the Japanese hiragana. It also does not have complex signs encoding major syllable constituents, as can be found in English (e.g. the combination of <letter i + consonant + letter e> in words like *strike, mine,* or *bite* can be considered as a complex grapheme encoding the rhyme section of a syllable). But apart from systematically encoding syllable nuclei, the German writing system reflects syllabic structures in some additional ways. Their common function is the characterization of syllable boundaries or transitions:

- If two syllable nuclei adjoin, they are graphemically separated by the letter <h> that (standard German) has no phonological correspondence: *gehen* (to go), *drehen* (to turn). The reader is thus given the information that the word consists of two syllables.
- Syllable joints or rather ambisyllabic consonants are systematically encoded by doubling the consonant letter: *Zimmer* (room), *rennen* (to run), *hoffen* (to hope).
- German hyphenation rules always respect syllable boundaries (in contrast to the English system). An important aspect of this subsystem is that it is not based exclusively on phonological information, as can be seen from the following examples:

wirk-lich   vs.   *bek-lagen* (really vs. to lament)
wir-klich   vs.   *be-klagen*

All four hyphenations would result in phonologically correct syllabifications, but only two of them are allowed in the orthographic system. *bek-lagen* is wrong, because onsets of prefixes and stems have to be preserved (*klagen* in this case), whereas onsets of suffixes do not. *wir-klich* is wrong, because, inside the stems and to their right end, a special rule has to be applied: If possible,

new hyphenation segments have to begin with exactly one consonant letter (in some cases with one grapheme).

These examples demonstrate two facts: 1. Though the German writing system is basically an alphabetic system, it reflects syllabic word structure in some important ways. 2. The specific ways of orthographic encoding are not exclusively based on phonological information. Instead, orthography is based on a partly specific and autonomous rule system.

If we now consider writing, compared to speaking, there are no directly observable structures in motor execution. Certainly, syllables do not deliver a frame for the organization of graphomotorics as they do for articulation in speech production. There is relation at the motor level between individual letters as there is between intrasyllabic vowels and consonants. If there are any references to this structural level, they must be looked for at more central cognitive processes. In this section, we will present the results of studies addressing the role of the syllable in written word production utilizing various methodological approaches.

As was reported in the morpheme section, the largest delay in the time course of word typing occurs when a new morpheme and a new syllable start conjointly. The effect size is not necessarily due to an addition of morpheme and syllable structure, but may be determined by the fact that, at these positions, basic lexical word constituents start (see section 3. Morphemes). Independently from morpheme onsets, we found a very consistent syllable effect in all our experiments (s. Will et al. 2003a, 2003b). When a new syllable commences, there is a significantly longer delay than at pure letter transition.

The first question arising from the syllable effect must address whether it is a side effect of articulatory or acoustic characteristics of language. Some results can clarify this issue: As found by Will et al. (2003a), when subvocal articulation is suppressed, that is, when a tone is sung whilst writing, words are still written in a syllable 'rhythm' (s. Will et al. 2003b). This indicates that the effect is unlikely to be produced by subvocal articulation accompanying writing. If the effect depends on phonological processes in some way, the interrelation must take place at a more central level.

In a study with hearing impaired participants Nottbusch et al. 2003a showed that this group of people wrote with almost the same syllabic patterns as unimpaired writers. In this study, the hearing impaired had suffered from a complete or very severe hearing loss from birth and so they certainly do not have the same kind of phonological representations of words established on the basis of spoken language experience as hearing people have. They may possibly have acquired a minimum amount of phonological information through kinaesthetic feedback in articulatory training and lip-reading. But this can in no way be equivalent to the lifetime input of auditory information that the hearing have. Accordingly, the hearing impaired must have acquired information on syllabic structures in written word production that is more or less independent from phonological information associated with the spoken language experience. As the time course of their typing is not fundamentally different from that of non-impaired subjects, these results tend to support the assumption of a syllabic structure that is independent of phonological processes, at least independent of those phonological processes established on the basis of spoken language experience. Obviously, it is, at least as far as the competent writer is concerned, an autonomous structure of the graphemic processing system.

In tracing the possible relation between effects of syllabic processing and phonology one might ask for the influence of other suprasegmental factors such as accents: Does the distribution of accents exert any influence on the time course of written word production? Apparently not (s. Will et al. 2003a). This can be seen as a further indication of the independence of graphosyllabic organization from phonosyllabic information.

The main focus of research on the relation between spoken and written language can be characterized by the concept of phoneme-grapheme-relations. According to this idea the orthographic word form is delivered either by the lexicon or via stepwise translation of the phoneme sequence of the phonological word form into the sequence of graphemes (e.g. Patterson, 1988?). As in these

models syllabic units are of no major importance, an information exchange between phonological and orthographic wordforms can take place either at the whole word level or at the segmental level. The question of how writers synchronize written and oral output was tested in a dual task experiment in which subjects were) asked to write and speak words simultaneously (Weingarten 2001a). It could be shown that synchronisation between the two output modes takes place only at syllable onsets. Here, the faster oral output slowed down by lengthening of sounds until the written output has finished the syllable as well. Subsequently a new syllable is started simultaneously in both modes. On the other hand, there seems to be no intrasyllabic synchronization between written and oral production. Furthermore, the additional cognitive load of the dual task in comparison with single task writing leads to increased delays in typing only at the beginning of a syllable and not intra-syllabic. In this case of a 'forced synchronization' between oral and written word production competent writers use the syllable boundaries as the place for synchronization. Although we cannot exclude the possibility that writers are able to synchronize at the grapheme level as well, this is not their spontaneous choice. This result hints at very stable and to a certain degree autonomous graphosyllabic units that do not exchange information with phonological processes at a subsyllabic level.

Another question that can be raised is, whether the syllabic structure of a word is determined by information stored in the lexicon. Three of our results do not support this assumption. First, we found the effect in pseudowords in just the same way, as we found it in ordinary words (see Will et al. 2003b). Syllable beginnings caused a significantly longer delay compared with other letter transitions. As this delay was roughly of the same size as the delay in ordinary words, we have no hint as to whether the syllabification processes in pseudowords are fundamentally different from those in ordinary words. These results support the assumption that the syllabic rhythm is not necessarily based on information stored lexically. Instead, it seems to be generated post-lexically. Secondly, further support for this assumption comes from the result that the syllable effect does not correlate with word frequency (Will et al. 2003b). As word frequency effects are usually considered as indicating access to the word-form lexicon (see section 3), the absence of this effect is more in favour of a post-lexical generation mechanism. Finally, in this study it was shown that word length does not exert any significant influence on syllable initial delays. This also hints at a certain independence of the syllable structure from aspects of the whole word as they are delivered by the lexicon. As no effect of syllable frequency on syllable initial keystrokes was found, we assume that the syllabification is accomplished by a rule based mechanism and not by a listed syllabary.

With these indications of syllables being a major processing unit in written word production, it is now necessary to look for syllable constituents as processing units on the next hierarchical level. In phonology, there is still an ongoing debate over the constituent structure of syllables (Eisenberg, 1998: 100). According to a widespread assumption, the syllable can be divided into onset and rhyme and the rhyme section again into nucleus and coda. An application of this model for time measurements in written word production predicts that more complex constituents will result in longer delays at their beginning than shorter ones, other factors being under control. This hypothesis is supported for syllable onsets in Will (2003b). If a syllable onset consists of two letters, a significantly longer syllable initial delay was found than for onsets with one letter. This effect was shown to be independent from overall syllable length. On the basis of the McKay model (1993) the assumption seems to be justified that the syllable is split into onset and rhyme. The assumption of a further division of the rhyme section into nucleus and coda has not yet been corroborated by time measurements.

At this point a major difference between the investigation of oral and written language production has to be noted. Whereas the effect of onset complexity reported by Santiago et al. (2000) is based on data on word initial syllables, in written word production we traced and found the effect at within word syllable boundaries. Therefore, both results cannot be directly compared and leave open the question if both production modes differ in respect of the point in time when information provided. Nevertheless, we can state that in written word production planning processes are not

finished while the motor execution is already advancing. This planning does not proceed in a step by step mode of segmental elements, but on highly differentiated hierarchical levels.

Finally, if a syllable consists of more than four letters, we found a further peak in the time structure at the letter positions three, four or five. There seems to be a certain degree of flexibility of the exact placement, possibly depending on the syllable length. Interestingly, this observation agrees with findings of Ostry (1983), who reported a maximum at the fourth character position[6]. These findings hint at a limited capacity of the motor buffer that possibly has to be reloaded after processing three to five letters. In many cases the syllable meets these capacity limitations quite well, and we can speculate that one source of the syllable effect might be a adjustment of an output unit to limitations of the motor buffer on the one hand and the best fitting linguistic unit on the other hand: the syllable. Only in the case of extreme misfits – if the syllable is to long – the syllable has to be split into pieces that can be managed by the motor buffer.

By asking for the origin of the syllable effect apart from phonological processes, it can be hypothesized that it is a side effect of the German word division system, which is, as was said earlier, related to the syllable structure. As English hyphenation does not necessaryily respect syllable structures, but, in some instances, gives a preference to the morphological structure, an experiment with English words and Australian English participants was conducted (Will et al. 2003b). The results also showed a significant effect of syllable boundaries on the time course of typing, which is not in support of the hypothesis, that the syllable effect is caused by a language specific hyphenation system.

 Our analyses of the impact of syllabic structures on the time course of written word production can be summarized as follows: Syllabic word structure determines a processing unit in written word production that can be ranked on the second highest sub-word level, just below subword lexical units that were characterized as SM-units in the previous section. Syllables in written word production seem to be generated postlexically by a rule based mechanism that does not necessarily rely on phonological processes. Time measurements indicate that syllable onset and rhyme may be processed as sub units.

Another important methodological approach, in research on language production in general, and written language production in particular, is to be seen in error analysis. Different types of errors - exchange, substitution, shift, addition, omission - hint at specific cognitive processes. If, in the case of exchange or substitution, the to-be-expected element and the misplaced element belong to the same abstract class, e.g. syllable onset, this can be taken as evidence for a processing unit represented by the abstract class. If a vowel is nearly always substituted by another vowel, this indicates a level of representation that generally demands the placement of a vowel without having already defined the specific vowelThe distribution of additions, omissions and shifts can be interpreted as indicating the stability of representational levels.

As far as oral language production is concerned, there is a widespread consensus that patterns of error distributions give clear evidence of hierarchically ordered syllables as processing units. It was shown that syllable onsets are frequently exchanged with other syllable onsets and syllable nuclei with other nuclei (e.g. MacNeilage 1998). On the other hand, some recent publications on errors in written language deny the syllable to be a processing unit in this mode. MacKay (1993), MacNeilage (1998) and Berg (1996, 2002) conclude from their studies that written word production is based on an "impoverished representation" (Berg, 1996). According to Berg (2002) the error distribution seems to be at random, giving no evidence for either syllabic constituents or whole syllables as processing units in written language production. MacNeilage (1998:503) states:

> "Any typist knows that, in contrast with spoken language, exchange errors occur not between units with comparable positions in an independently specified superordinate frame structure, but simply between adjacent letters. This is true whether the units are in the same syllable or in different syllables."

Before returning to error analysis in the next section, a comment on the empirical basis of these studies must be made. The data basis of some studies denying any syllable effect is to be considered

as very restricted. Berg's analyses cover only his own writings (Berg 1996) and published journal articles (Berg 2002), which means that the latter texts have undergone many revisions. Logan (1999) (this work will be discussed in the grapheme section) investigates reconstructable errors of a (single) secretary. One author even 'invented' an exchange error across syllable boundaries and presented that as evidence against the existence of syllabic frames in typing. Some of these empirical weaknesses are discussed in Berg (2002) and certainly the results are far from being representative and not all of them reach the standard of the existing corpora of errors in spoken language..

Another difficulty in written language, and especially typing, has to be seen in the categorization of errors. It cannot be doubted that typing is extremely prone to motor based errors and a large number of the observed errors are usually of this type: Instead of the target key a neighbouring one is pressed or two keys are pressed simultaneously. Also, many exchanges of adjacent letters belong to this type, as can be seen from the fact that they do not occur in handwriting. If error corpora consist to a large extent of these motor errors, the impression of an "impoverished representation" in written word production is quite unsurprising. But considering the extremely large number of these types of errors, which becomes evident by comparing typing to the number of errors in oral language production and, considering the point that many of theses errors are not due to orthographic weaknesses, it can be inferred that they cannot be attributed to central processes of written language production. Instead, what Berg calls "impoverished representation" is exclusively true for the executed motor patterns in typing. An investigation of the more central cognitive processes in written word production has to distinguish between errors cause at the level of motor performance and those originating more centrally.

In our own studies (Will et al. 2003) we relied on spontaneous und uncorrected typing and separated errors that could be explained as faulty motor performance (i.e. errors involving neighbouring keys on the keyboard). The analysis of the remaining data revealed a strong tendency of avoiding exchange errors across combined syllable and morpheme boundaries. Though further studies on this subject have to be done, the hypothesis of a syllabic frame finds support in our error distribution analysis. Certainly, the scope of exchanges in written word production seems to be smaller than in the oral mode as can be seen from the fact that classical spoonerisms of the type *Baumkuchen > Kaumbuchen* are extremely rare. But this does not mean that there are no sub-word structures. Instead, error distributions in typing are in accordance with the syllabic pattern found in time measurements.

5. Graphemes

Graphemes are usually considered to be the smallest functional units of written language. The most common definition is that graphemes are the corresponding units of phonemes in spoken language. Another concept aims at defining graphemes without referring to spoken language, just by considering their functional properties for the written language system itself, as minimal graphic signs distinguishing word meaning in a particular language. Though these two procedures may not lead to fundamentally different sets of graphemes, their respective implications are of major importance, with the first case presupposing a dependency of written language on spoken language and the latter case an autonomy of written language.

In an ideal writing system graphemes would be identical to the basic graphic signs – that is letters in languages using an alphabetic writing system. But due to historical constraints, graphemes are quite often not identical with single letters. At least two factors can account for this situation:

1. In the case of the German writing system that adopted the roman alphabet, appropriate signs for some phonological differences of German were not delivered by its ancestor; e.g. in order to represent the phoneme [ʃ] the German writing system 'invented' the polygrapheme <sch>; furthermore, additional letter combinations were necessary to represent the phonological opposition between short and long vowels.

2. Other sources for polygraphemes are asynchronous historical developments of oral and written language, mainly caused by the more conservative character of written language. A prominent example of this is the monopthongization in oral language (e.g. in German: [ɪɛ] ? [iː]), whereas written language preserved the diphthong representing letters (<ie>), but reinterpreted them as representing a single long vowel in present day German. Accordingly, this letter pair has now to be considered as one grapheme, whereas in middle high German it comprised two graphemes. As a result, we now have graphemes comprising one, two or three letters (even more in the English writing system).

These factors resulted in orthographic systems, where phonological wordforms could no longer consistently be inferred from the letter sequence and vice versa. An important aspect of this dissociation is the evolution of an intermediate system of graphemes, sequences of 1-3 letters in the German writing system, defined by functional relations to the phonological wordform. The degree of this dissociation is sometimes expressed as orthographic depth. The English and French writing systems are considered to be orthographically deep, whereas Finish, Italian or Spanish are said to be orthographically shallow, with German being in the middle. An important aspect of orthographic depth is the phonological transparency of a writing system: Deeper systems are usually phonologically opaque to a certain degree, whereas shallow systems are more transparent.

This relative dissociation of letters and phonological units in some writing systems poses the interesting question of whether multi-letter graphemes are also treated as units in the processing of written language. It could be hypothesized that the skilled reader and writer has developed a functional representation above the letter level, which gives him the advantage of processing certain letter combinations in the correct way, without being mislead by their individual phonological interpretation. A further question is whether graphemic units are of importance in the case of non-phonologically mediated processing of written language, which is commonly assumed for high frequency words. It is important to note here that the processing of graphemic multi-letter units leads to the assumption of a different cognitive architecture than the one used for the processing of letter groups that are formed on the basis of frequency distributions. The notion of graphemes implies a rule based mechanism, whereas frequency distributions are more in favour of connectionist models (see Pinker (1999) for a general discussion). For example, <er> is a highly frequent letter combination in German, whereas <ew> is infrequent. Nevertheless, neither of them constitutes a grapheme. <qu> on the other hand, is a low frequency item but must be considered as a grapheme. Frequency and the graphemic function of letter groups therefore constitute different sets of units.

Apart from frequency patterns, one can ask for functional units such as multi-letter graphemes. In the literature dealing with the German writing system, there is not yet a complete consensus, as to which letter combinations have to be considered as graphemes (see Eisenberg 1998; Nerius 2000). Without going into the details of the linguistic discussion, we will consider the following letter combinations as candidates for graphemes:

vowels: <ie>, <VV>, <Vh>
diphthongs: <äu>, <eu>, <ei>
consonants: <ch>, <ck>, <dt>, <ng>, <sch>, <tz>, <CC>

(<VV> signifies vowel doubling, <Vh> vowel plus letter <h>, <CC> consonant doubling; <qu> also belongs to this group, signifying a consonant-vowel combination; finally, <th> and <ph> are more or less restricted to foreign words.) A common property of these combinations is that the specific function of the whole group goes beyond the functions of its respective parts. In our research three types of empirical approaches addressed the question, whether these letter combinations constitute processing units.

1. According to the assumed relation between processing units and temporal patterns, the hypothesis can be put forward that, at the beginning of a multi-letter grapheme, there is a comparatively larger delay. This should occur because the whole letter sequence of the grapheme has to be

prepared (not just the next letter). On the other hand, the subsequent letter(s) belonging to that grapheme should be produced faster, compared to a corresponding single letter grapheme, because it/they already should have been prepared in parts at the beginning of the grapheme. Consider the following example (1):

(1) a.   *Freude*   [ˈfʁɔɪ.də]   'pleasure'   vs.
     b.   *Fremde*   [ˈfʁɛm.də]   'foreign parts'

In *Freude* <eu> has to be considered as a di-grapheme, whereas the letter sequence <em> in *Fremde* comprises two mono-graphemes. According to the hypothesis, the delay before the third letter in *Freude* should be larger than the delay before the third letter in *Fremde*. This hypothesis was tested in a word copying task for the following multigraphemes: <eu>, <sch>, <ng>, <CC>, <VV>, <äu>, <Vh>, <ei>, <ie>, <tz> (see Weingarten 2003). In the overall comparison, multi-grapheme beginnings were found to cause slightly longer delays than single letter graphemes, but this difference was not significant. On the other hand, the second letter of a multigrapheme was written with a significantly shorter transition time than the letter following the mono-grapheme in the corresponding word pair. This certainly supports the hypothesis, but a weakness in this result must be hinted at. Whereas, with respect to the first letter, possible effects of frequencies of letter pairs are under control (in both (1a) and (1b) we inspect <e> in the letter pair <re>), this is not, and certainly cannot be, the case for the forth letter in the word, which is the second letter of the di-grapheme. In (1a) we look at <u> in the pair <eu>, and in 1b we look at <m> in the pair <em>. Here we have an interference with the specific conditions for writing the letter <u> vs. <m>. But, as a set of different types of letter combinations were investigated, we are not just dealing with a di-gram effect (see section 2). Taken the weakness in the data into consiceration , it is nevertheless quite implausible to completely deny the multigrapheme effect.

When we take a closer look at the different types tested, we can see that obviously they do not all behave in the same way. In eight out of ten cases we found longer latencies before the first letter of a di-grapheme than before the corresponding mono-graphemes: <eu>, <sch>, <ng>, <CC>, <VV>, <äu>, <Vh>, <ei>. In two cases the mono-grapheme condition yielded longer latencies: <ie>, <tz>.

2. In a different methodological approach we designed an experiment with a word completion task (for details see also Weingarten 2003). The material consisted of word pairs made up of the types presented in example 2:

(2)   a.   *Leute*   [ˈlɔɪ.tə] 'people'   vs.
      b.   *Stute*   [ˈʃtuː.tə]   'mare'

In *Leute* the letter <u> is the second part of a di-grapheme whereas in *Stute* it is a mono-grapheme. Participants were presented with a randomized list of words made up of pairs, like those just mentioned. First they saw the whole word on the computer screen and subsequently the first part of a word: *Le* in the case of *Leute* and *St* in the case of *Stute*. The instruction was to complete the word, which meant that in both conditions they had to write *ute*. Whereas in *Leute,* the completion has to start inside a di-grapheme, in *Stute* it can start simply with a new grapheme. We therefore expected that the completion of *Leute* would cause a longer delay, because not only the letter <u>, but the whole grapheme, has to be activated, that is to say the preceding letter <e> and the function of the entire grapheme <eu>.

With respect to the whole set of graphemes, we found a difference in the way expected, but it was not significant. In a post hoc test the graphemes investigated were split up into two groups on the concept of 'phonological compositionality': The first group comprised graphemes that allowed to directly infer their phonological equivalence directly from their elements: <CC>: [C], <VV>: [Vː], <ck>: [k] and <tz>: [t͡s]. These graphemes were referred to as 'phonologically compositional'.

In the case of <eu>: [ɔɪ], <sch>: [ʃ], <ng>: [ŋ], <äu>: [ɔɪ] the phonological value of the whole grapheme is totally independent from the included letters. They were referred to as 'phonologically non-compositional'. In the non-compositional group completions started significantly later.

A recent study on the reception of written language generally supports the grapheme hypothesis (Rey et al. 2000). Though phonological compositionality was not tested, most of the items in this study belonged to the non-compositional type introduced previously. In a letter detection task on French and English words, it was shown that single-letter graphemes are easier to detect than single letters embedded in multi-letter graphemes. It can be assumed that in the case of multi-letter graphemes the immediately processed whole unit has to be split up before accessing the embedded letters. The authors presume that graphemes are processed as perceptual units by the reading system. This methodological paradigm seems to be an exact analogy on the reception side to the above mentioned word completion task. In both cases, complex graphemes have to be split up in order to act on a single component letter. This operation of splitting the multi-letter graphemes is time consuming compared with an action on a single-letter grapheme.

To summarize, we assume that there is a tendency to group letters as functional units called graphemes, if they have a "non-compositional phonological meaning". Cognitive processes in these aspects of the written mode are apparently easier to accomplish, if they do not rely on phonological word forms.

3. A third methodological approach to investigating the grapheme hypothesis in written word production is error analysis. Similar to the results reported in the syllable section, some recently published articles denied the relevance of this linguistic level in written word production. Two aspects shall be discussed here, namely, the doubling of letters and a representational level that assigns to individual graphemes a vowel or consonant status. As far as the doubling of letters is concerned, several studies (e.g. Berg 2002, Logan 1999, Will et al. 2003a) agree on the observation that doubled letters are substituted, preferably, by other letter repetitions. This is in accordance with the above mentioned results on time structures: The second letter in a geminate letter pair is typed faster than in a non geminate context. This indicates that geminates are planned as a single processing unit. Looking for the processing level at which this unit operates, two possibilities and a combination thereof can be conceived of. First of all, it could be a basic motor pattern that has encoded the letter type and the repetition information separately. In making an error the letter information can be disturbed, whereas the repetition information remains preserved. Alternatively, the same dissociation could occur at the more central level of graphemic encoding. In this case, the linguistic function of letter doubling would also be encoded. (In the German writing system doubled consonants represent a syllable joint and doubled vowels the lengthening of the vowel.) This question can only be decided on the basis of a combination of this error type and errors persevering or changing the vowel or consonant status of the affected letters. If doubled vowels are preferably substituted by other vowels, and consonants by consonants, this would hint at a grapheme level, otherwise there were no indications for linguistically functional units. To investigate this question, we need much more data.

As far as the preservation of the vowel-consonant status is concerned, MacNeilage (1998, 503) writes: "In addition, unlike in speech, there is no constraint against exchanging actions symbolizing consonants and actions symbolizing vowels." Similarly negative results are reported by Berg (1996, 2002). Again, this is at variance with the results from our own analyses (Will et al. 2003a), which are based on data from many writers and a separation of motor performance and non-motor performance errors. . In these studies we found a significant preference of vowels being substituted by other vowels and consonants by consonants. This result is in accordance with the results published by Logan (1999). Accordingly, we assume that the hypothesis of a processing level representing the vowel-consonant status of a grapheme seems to be justified.

Our studies on written word production can be summarized as giving converging evidence by different methodological approaches for graphemes as production units. Nevertheless, it has to be admitted that studies on production are still less advanced than reception studies.

6. Outlines of a model of written word production

In this section the results of our studies on written word production shall be summarized in a constituent model representing the main linguistic units and their hierarchical order in written word production (see figure 4). Constituent models are in accordance with standard linguistic models of word or sentence structure and as such they do not give any information in the temporal domain. As this information is of major importance from a processing point of view, the model has to be enhanced with respective information, specifying when constituents are planned in the time course of word writing. The proposed model focuses on linguistic units and therefore it is unspecific with respect to any nonlinguistic factors.
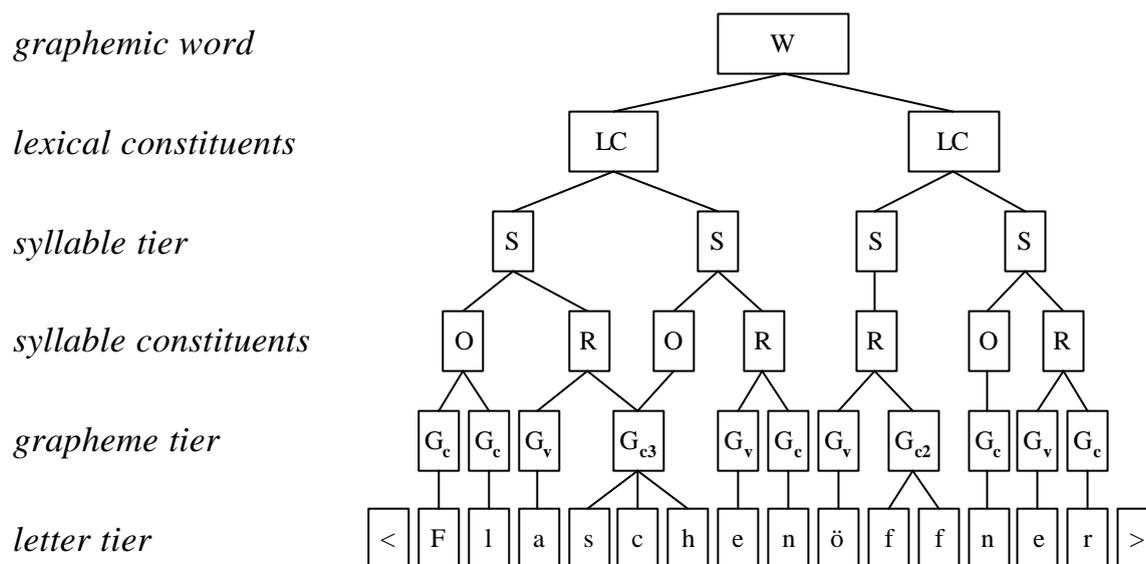

Figure 4: Constituent model of written words. W = graphemic word, LC = lexical constituent, S = syllable, O = onset, R = rhyme, G_C = consonant grapheme, G_{Cn} = consonant grapheme with n letters, G_V = vowel grapheme

The basic idea of the constituent model is that written words can be represented in a hierarchy of different tiers. At the top level there is the *graphemic word*. The relationship of graphemic words to other conceptions of word such as phonological, lexical or grammatical words is not part of this model, though it would have to be specified in a general model of German orthography (including e.g. conditions for capitalization, hyphenation and word division). The relationship between graphemic and other word models may differ between writing systems as can be seen by the following example: <Taxifahrer> is graphemic word in German, whereas <taxi driver> in English comprises two graphemic words, though, in both languages, it refers to only one grammatical word.

The immediate constituents of graphemic words are *lexical constituents*. A word can consist of one or more lexical constituent. These parts of a word are delivered by the lexicon, in other words, they require a (re-)access to the mental lexicon before motor execution, either word initially, for the first lexical constituent or word internally for the subsequent constituents. Whereas in the proposed model this hierarchical level is defined from a processing point of view, it is not yet perfectly clear, how it can be matched onto structural linguistic units such as morphemes. Certainly, there is a strong overlap with the category of root morphemes, but affixes can also represent lexical constituents as can be inferred from word frequency effects. However, prefixes and suffixes are affected to differing degrees, presumably due to the differences concerning a) the timing sequence, i.e. they emerge ahead of the associated stem and b) the emergence of a following stem is, in contrast to suffixes, obligatory. In addition, suffixes have been shown to serve as a lexical constituent only if

they begin with a consonant, i.e. the word is not re-syllabified. It should be noted that for these reasons morphemes do *not* appear as units in this model, though they are word constituents from a linguistic point of view. There can be no doubt that in a processing model they must be taken into account as well, because, for example, inflectional adaptation of a word to its syntactic environment is of major importance to word production. But as long as we do not have any traces of morphological construction processes in the time course of written word production we do not integrate this structural level into our model.

The next level is the *syllable tier*. Syllables in written word production are dynamic parts of the aforementioned lexical constituents in a way that they split up these units into the number of syllables they include. Accordingly, if a lexical constituent includes only one syllable there will be no further division, if it includes two syllables, it will be split up into two processing units of this kind, and so on. Graphosyllables, as they will be referred to here, are supposed to be formed post lexically. We cannot yet say whether this process is accomplished by a syllabary, that is a stored list of syllables, or by a rule-based mechanism.

The next level on the way from top to bottom comprises the *syllable constituents* onset and rhyme. Though we only have empirical evidence for onset complexity, there must be a type of unit for the 'rest' of the syllable, and that is traditionally denoted as the rhyme section. Another implication of the split between the onset and the rest of the syllable is a differentiation between vowel and consonants, because the only way to determine a syllable onset is by separating the consonants preceding the vocalic nucleus of a syllable. This information must be delivered to the syllable constituents by lower level constituents which will be the grapheme tier in the proposed model.

Once the categorization of vowels and consonants comes into play, a split of the rhyme into rhyme constituents, that is a vowel and a consonant section, can be assumed. In terms of phonology they are referred to as nucleus and coda. But as was reported previously, neither time measurements nor error analyses give any evidence as to rhyme constituents of this type. Another motivation for assuming these rhyme constituents could be derived from pseudoword writing. As was shown in Weingarten (2001b), German writers apply the orthographic rules of writing ambisyllabic consonants by letter doubling very consistently when writing pseudowords. This can only be done, if a phoneme has previously been categorized as representing a syllable coda and an onset at the same time. Nevertheless, as at present neither error analyses nor time measurements indicate such a split, we do not consider it in the proposed model at the present time.

The next level comprises the *grapheme tier*. We assume that there is a post lexical storage of graphemes that accounts for a treatment of multi-letter graphemes as processing units. Proposing such a level of representation does not imply that the sequence of graphemes is necessarily generated post lexically. Certainly, in the case of high frequency items the graphemic word form is directly delivered by the Graphemic Output Lexicon and not by any kind of conversion mechanism. Nevertheless, even here the grapheme tier of representation seems to be operant. In the proposed model, the grapheme tier also includes information on the vowel or consonant status of a single grapheme.

The terminal nodes in this model are represented by the *letter tier*. The writer of an alphabetic language has a storage of the letters of his writing system. This storage is part of a grapheme-letter conversion system, a rule system that especially (specifically?) applies to multi-letter graphemes. The letter storage may also give rise to frequency effects resulting in different letter transitions times. As this digram effect is on the one hand determined by single letter frequencies and on the other hand by digram, trigram and higher n-gram frequencies we have to assume that the letter storage is not ordered as a list of isolated items but as a network.

The proposed model only accounts for some of the central linguistic processes of word production. It does not cover motor processes and it also does not represent the processes of generating the graphemic word form. Instead, it is a model of the hierarchy of processing units with its relation to the orthographic system still to be elucidated.

A fundamentally different constituent model of written words was recently put forward by Berg (1996, 2002), summarizing his studies on errors in typewriting, handwriting and oral language production. According to Berg's model word writing is based on a "weak structural representation" with almost no subword levels of linguistic processing units. The only intermediate level between the whole word and the letters is the "skeleton tier", indicating whether a letter is to be written once or twice. As Berg (2002) explicitly investigated only submorphemic errors, the proposal of a model covering the whole word range (Berg 2002: 200) must be called rather premature. Furthermore, his denial of syllabic and subsyllabic processing units must be rejected in the light of our data. To sum up, the model proposed here is in almost every respect a rejection of Berg's model, especially in asserting a highly structured representation determining written word production.

As was said before, the constituent model is unspecific with respect to the temporal order so it has to be extended in this regard. The most important result from our studies is that at the beginning of the motor execution of writing a word, the constituent structure is not yet completely specified in the motor buffer. Instead, information about the whole word is being prepared, as can be inferred from the positive correlation between word length and word initial latency (Will et al. 2003a). Furthermore, some general information about the syllable structure must be processed, as the initial latency correlates positively with the number of syllables (Will et al. 2003b), whereas the later parts of a word are only roughly specified: With respect to the subsyllabic units, the first syllabic subword constituent is already filled segmentally, as can be seen by the positive correlation between word initial latency and length of the first syllable. The same pattern can be found for the subsequent subword frames (Will et al. 2003b).

A logical alternative to constituent structure regularly used in linguistics is bracketing. Accordingly, the proposed model can be directly transformed into the following expression:
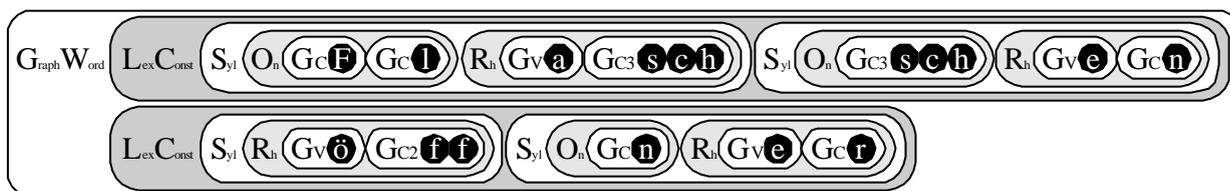

Figure X: (The expression of ambisyllabic consonants is quite inconvenient in brackets. It is accomplished here by dual printing of <sch>).

Metaphorically, the bracketing structure can be expressed in the concept of frames and segmental fillers with frames denoting brackets. This metaphor has been used at various times in language production models, recently by MacNeilage (1996, 1998). With respect to speech production MacNeilage (1996: 499) suggests that "syllabic 'frames' and segmental 'content' elements are separately controlled in the speech production process". As far as typing is concerned, MacNeilage, in accordance with Berg (2002), denies the existence of a frame and filler mode of organization (MacNeilage 1996: 503). We hope to have given enough evidence against these conceptions of word writing.

7. Further perspectives

The analysis of the time course of written word production has proved to be a powerful instrument that can give many insights not only into motor processes but also into underlying cognitive processes. Due to the fact that, when starting to write a complex word, not all of the necessary information is already specified in the motor output buffer, cognitive processes are still on-going whilst motor processes are being executed. These processes can be observed as characteristic patterns of delays in the time course of word writing and can be differentiated from peripheral determinants

such as keyboard layout or motor processes. This situation leads to an enriched databasis for the analysis of written word production in comparison with the analysis of spoken word production. Until now there is no empirical evidence that the time course of the speech signal is determined by cognitive processes going on during motor execution. In most studies time measurements in spoken word production are confined to initial latencies (reaction times), prior to the beginning of the motor execution.

Though the basic processes of written word production have now been clarified, a number of questions still remains unanswered. An ongoing discussion in written word processing is the role of phonology. Whereas reading research, after many years of debate, has more or less reached a consensus in a dual route model (e.g. Coltheart et al. 2001), assuming an independence of word reading from phonological resources in high frequency items, writing research is less advanced. Nevertheless, our results on temporal structures in the writing of normal and hearing impaired persons, as well as our error data, support the hypothesis that writing can be, at least to a certain degree, independent of phonological processes. This hints at a parallel architecture of production and reception models. In our future research we will focus on the writing processes of deep dysgraphia patients in order to find out, whether they also display a syllabic pattern in their time structures. If this turns out to be the case, this pattern could not be traced back to phonological processes, due to the phonological impairment in dysgraphia. Accordingly, we would have to assume an autonomous grapho-syllabic structuring that does not rely in a direct way on the activation of phonological word forms.

Another issue that merits further investigation is the question when and where morphological processes take place, i.e. when and where they are applied to stems forming new words or word forms. As yet, we were not able to find any traces of morphological processes in the time course of the production of isolated words, if morpheme onsets do not coincide with syllable onsets. In German, this coincidence is always the case for stem morphemes, whereas inflectional and derivational morphemes do not always result start with a new syllable. Therefore, as reported in the previous section, compositional and derivational processes have to be investigated with the methodological paradigm developed thus far leading to interesting differences between storage and computation of these aspects of word production being discovered. On the other hand, it has to be asked when, in the time course of written word production, planning of inflectional morphemes takes place. It should also be kept in mind, that not all processes of language production necessarily have to affect the time course of writing. Until further reliable counter-evidence is available, a guiding hypothesis can be to search for delays caused by inflectional processes.

Obviously, inflections are not planned locally at the point where the inflectional morpheme starts. This can be assumed with certainty. There seem to be two possibilities for where this planning may take place: a. if inflections are planned word initially, we expect an increased word initial latency in the case of morphologically marked word-forms in contrast to default forms. b. if inflections are prepared somewhere in the phrase the word belongs to, morphological planning may be a distributed process, slowing down the execution over a larger area of that phrase. These changes will be difficult to detect empirically, as there might only be very slight decreases in production rate. In any case, to investigate inflectional morphology, the scope of investigation has to be extended from the level of isolated words to the phrase level.

In addition to inflectional morphology, the investigation of phrase production time course, sentences or even complete texts opens up a wide range of new questions. Just as word production results in characteristic temporal patterns informing us about cognitive processes, syntactic and textual planning are expected to result in comparable characteristic temporal patterns. First results are presented in Cummins et al. (2003) and Nottbusch & Weingarten (2003). Here, the time courses of the production of two types of syntactic structures, coordination and subordination, were analyzed and shown to reveal different patterns.

An important issue in writing research is the investigation of teaching and acquisition processes. In many school programs the teaching of writing starts at the segmental level of letters (not even graphemes) and their relation to sound units. But, as can be seen from the results presented, compe-

tent writing involves a hierarchically organized processing strategy that is, at least to a certain degree, independent of phonology. Therefore, the question arises as to how a learner develops these strategies and how this can be supported by instructional means. One important aspect seems to be the assembly of segmental units into graphosyllabic units, thus developing an intermediate level of processing between the word and its segments. Obviously, frequency determined letter groups do not serve as optimal processing units, instead, syllables are assembled; in other word: units that are oriented towards structural properties of the respective language. It has to be noted that this way of written word production is not taught in writing classes. Alternatively, a learner must develop this skill on the basis of his/her own knowledge and practice of language. Some initial results how this is accomplished were presented in Weingarten (1998). In that study it was shown that, at the beginning of the acquisition process, writing is not structured according to a clear syllabic pattern. Instead, this rhythmic organization gradually evolves, probably as a consequence of greater writing competence. Further studies have to elucidate the driving forces behind this development and especially how the increasing independence from phonological processing is accomplished.

Finally, an extremely promising perspective is the combination of time analysis of writing data with neurophysiological methods such as brain imaging. At present functional neuroanatomy of writing is still relatively unexplored (see e.g. Katanoda, Yoshikawa and Sugishita, 2001; Matsuo et al., 2000; Tagamets et al., 2000). Brain imaging studies can help to shed some light upon the relationship between oral and written language production by observing whether specific processes result in the activation of similar or separate brain regions in the two modes (see for instance the 'classical' study of Petersen et al. (1988). The subtraction methods used in studies of this type are based on a difference logic that requires a componential analyses of the functional organization involved in the experimental and control tasks. As Indefry and Levelt (2000) have pointed out, it is rare that such componential analysis is independently performed and tested e.g. by way of reaction time studies. The availability of the temporal analyses from our writing and typing data can serve as an important control and reference for such componential analyses of fMRI data. The experimental results presented above allow for an improved cognitive model of writing processes and also for some a priori hypotheses about how these processes might be implemented neurally. This, in turn, will considerably enhance the interpretation of future fMRI studies applying the subtractive method.

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Zesiger, Pascal, J Orliaguet, L Boë, and Pierre Mounoud

1994 The Influence of Syllabic Structure in Handwriting and Typing Production. In Faure, Claudie; Keuss, Paul; Lorette, Guy; Vinter, Annie, *Advances in Handwriting and Drawing: A Multidisciplinary Approach* (389401). Paris: Europia.

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[1]In fact, there are, apart from some special cases, no German words that contain a Vowel-Consonant-digraph that spans a pure morpheme boundary, i.e. VC-digraphs were used to compare SM vs. M vs. L type IKIs. Conversely, no German word containing a CV-digraph spanning a pure syllable boundary was found, i.e. VC-digraphs were used to compare SM vs. S vs. L type IKIs.

[2] Unfortunately, it remains unclear what the author meant by their terminus 'latency' as it is stated: "Insofar as the delay between the acoustical presentation of the task word and the onset of recording on the graphic tablet *has not been measured*, the latency represents only a part of the reaction time." (108, our emphasis) Concerning total writing times the effect of rule application is characterized by differences between subjects, i.e. movement times increased for (1) all letters (three participants), (2) the initial letter (another three participants) or (3) the letter preceding the locus of rule application (two participants).

[3] In order to a) fulfil the digraph criterion and b) to match the within-word position of the digraphs as far as possible, items of type (2) had to be prepared in two separate stimuli lists: one matching the items of type (1) and another one matching the items of type (3).

[4] The amount of intransparent words is much higher within the items with a high whole word frequency than in those of high base frequency.

[5] Participants were asked to delay writing until a 'go'-signal occurred 1800 ms after stimulus presentation.

[6]Here, it has to be noted that the average syllable length lies between 3 and 4 characters (in German as well as in English) and that the increased latencies found by Ostry (1983) in all likelyhood correspond with syllable boundaries.