title: Linguistic units, hierarchies and dynamics in word typing

auxiliary short title: Linguistic units

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Abstract

This study reports on five experiments in which English and German participants had to type words presented visually or orally or elicited in a picture naming task. In another experiment subjects were to type pseudo-words, and in the last experiment typing responses were delayed. In all experiments a highly significant increase of inter-keystroke intervals (IKIs) at positions that where either exclusively syllable (S) boundaries or combined syllable and morpheme (SM) boundaries was found. SM-type IKIs are significantly larger than S-type IKIs and influenced by word frequencies, indicating lexical dependencies. SM-type IKIs were found to be significantly longer for oral than for visual word presentation. This is taken as an indication that additional processes are involved in the accessing of graphemic word forms when words are presented orally. The fact that pseudo-words are also written with increased IKIs at syllable onsets indicates that at least one major component of the S-type IKIs is produced by bypassing the lexicon. The fact that augmented SM- and S-type IKIs are also found in the delayed typing task indicates that input into the motor system is constituted by sub-word units instead by fully specified words. As SM- and S-type IKIs reflect influences of different hierarchical levels of language processing, these findings suggest a processing architecture in which the peripheral motor system essentially connects at several hierarchical levels with central processing units.

1. Introduction

Language production finds its expression in distinct domains of human motor activities like speaking, writing and typing. Present day knowledge about the processing architecture underlying language production however mainly originates from studies on production of spoken language using three basic methodological approaches: speech error analysis, reaction time experiments, and the study of clinical–neurological cases (e.g., Butterworth, 1992; Dell, 1986; Garrett, 1975; Levelt, 1989; MacKay, 1987; Stemberger, 1985). It is generally held that the production process commences with conceptual planning which in turn leads to retrieval of necessary lexical information and to subsequent phonological encoding and translation into motor programs for execution. Although phonemes are considered to be building blocks of speech signals, experimental evidence (Levelt, 1989; Fujimura, 1990; Levelt et al., 1999) clearly indicates that they cannot simply be unstructured linear strings. It is therefore thought (e.g., Fromkin, 1971; Shattuck-Hufnagel, 1979; Dell, 1988; Levelt et al., 1999) that information retrieved from the lexicon consists of abstract, suprasegmental frame units. These are ‘filled up’ during the encoding process with fully specified phonemes and motor programs lead to segmental concatenation and coarticulation. (For alternative models see e.g. Öhman, 1967; Itô et al., 1995; Fujimura, 2000).

Despite a considerable number of studies on handwriting (for reviews see Askov et al., 1970; Peck et al., 1980; Graham & Weintraub, 1996), experimental research on cognitive and motor processes involved only started to intensify during the 1980s with the advances of digitized writing-tablets. A modified logogen model (Morton, 1980) to account for the organization of writing processes, was proposed by Ellis (1982) and Margolin (1984), based on clinical and experimental studies. One of the important elements in this model is the graphemic output buffer and it is assumed that this buffer, as well as all preceding higher level processing modules are common to all output modes, i.e. speaking, writing, and typing. However, more peripheral, subsequent modules, e.g. allographic selection and conversion, are thought to be mode specific. Information in the graphemic output buffer is probably multidimensional and, according to Caramazza and Miceli (1990), is thought to contain information about graphemes, C/V status, geminate features and graphosyllabic boundaries.

The increasing number of studies on handwriting contributed to the proposal of a psychomotor theory of handwriting by van Galen and colleagues (van Galen and Teulings, 1983; Hulstijn and van Galen, 1983; van Galen et al., 1986; van Galen et al., 1989; van Galen, 1991). This model is a strictly sequential-hierarchical one and assumes decreasing processing units. Central processing modules are further ahead of the real-time output than peripheral ones and, to avoid timing conflicts during processing, memory buffers are hypothesized to exist between all processing modules. It is further assumed that first a complete phonological code of words is specified and that this code is then translated into a graphemic code during the writing process. The resulting motor program is viewed as an abstract, non-muscle specific representation for the execution of ordered sequences of writing movements.

The early 1980s also saw a surge of studies on typing as skilled motor behavior which 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 written language production. One reason for this seems to be the widely held view 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 1969, Luria, 1966, Wernicke, 1886. For a review see Ellis, 1982). On the other hand skilled motor behavior studies have promoted the view that the motor system involved is to a large extent, if not completely, independent of higher cognitive language processes and timing and time structures in writing contribute little to their understanding. These approaches 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), this has only been analyzed with regard to the 'length effect' of different numbers of syllables on the execution of motor programs. Van Galen (1990) claims to have identified a syllabic influence in handwriting: syllable repetition seems to shorten initial latency (IL) 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 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 & Viviani, 1980) have been reported by previous studies.

Weingarten (1997) and Nottbusch et al. (1998) have recently forwarded further evidence that linguistic units do have an influence on the time structure of handwriting. The authors found a highly significant correspondence between the duration of pen lift-offs and linguistic types of grapheme boundary: significantly, lift-offs were longest at grapheme transitions that were at the same time new syllable and new morpheme starts. In a second experiment analogous results were obtained for discontinuous typewriting. The influence of linguistic units on the time structure in discontinuous typewriting following visually presented German words has been studied in more detail in a subsequent study (Will et al., 2001): Interkey intervals were found to depend significantly on the type of linguistic within-word boundaries (syllable and combined syllable/morpheme boundaries), and within-syllable interkey intervals were influenced by syllable frequencies and position within the syllable. The results of these studies are a clear indication that the time course of motor activities in typing is not independent of the linguistic processes of written word production. Therefore the analysis of the time structure of writing, handwriting as well as typewriting, might offer an interesting approach for the analysis of the processing architecture in written word production, at least in as far as the processes involved are reflected in the time domain.

The present study reports on five experiments that were set out to further explore these time dependent processes in typewriting and evaluate their contribution to the understanding of written word production. The first experiment was designed for native English speakers in order to allow for a comparison between the German (Nottbusch et al. (1998); Will et al. (2001)) and English language. To examine the influence of orthographic information on the time structure, the second experiment analyses word typing following oral word presentation and compares it with that for visual word presentation. The third experiment aims at identifying lexical components by comparing typing following visual word presentation and picture presentation. In order to further separate lexical from non-lexical processes, a fourth experiment was designed dealing with typing of pseudo-words, for which there are no lexical entries. As previous studies used a delayed writing paradigm the fifth and last experiment investigates the influence of a delay between stimulus presentation and typing on the interkey time intervals. This experiment will provide important clues about the link between peripheral motor processes and more central process in written language production.

Methodological considerations

The present 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, following the presentation of a signal.

Data types

This type of experiment gives two essentially different types of time information, initial latencies (ILs) and series of interkey intervals (IKIs). ILs are the time intervals between the start signal and the first keystroke and contain information related to processes operand during this time span. IKIs are the time intervals between successive key-strokes and contain information about processes active between key-strokes. In the present study we are concerned mainly with the analysis of the within-word IKIs.

Data distribution

It has already been reported (Shaffer, 1973; Gentner, 1983) that interkey intervals in typing experiments show markedly right skewed, non-normal distributions. However, for two reasons we abstain from applying non-parametric statistics. First, in the study presented here, we are not concerned with analyzing data from individual typists, but with revealing general tendencies in relation to certain speed groups. Therefore we are averaging the original measurements over subjects within each of the speed groups, each containing roughly the same number of typists. Resulting mean values can in turn be 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 seems 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.

Context effects

Due to the fact that language features set the conditions for the occurrence of characters in certain syllable positions there are language specific preferences for certain characters to appear in sub-syllabic segments such as onset and rhyme. This makes it extremely difficult if not impossible to control the distribution of characters with regard to syllable boundaries and within-syllable position if one uses normal language material. Furthermore, despite indications that single keystrokes are the basic units of motor performance in typing (Rumelhart & 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 word boundaries. If for example a character is typed with longer IKIs at syllable boundaries than at within-syllable positions, this could be due to a context effect: the character may be surrounded by different characters in the two contexts. However, Gentner (1983) has demonstrated the strongest influence is exerted by the immediately preceding character (reduction of variability of the IKIs (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.

Digraph sets

In the present study we are classifying interkey intervals (IKIs) according to ‘type of boundaries’: IKIs at combined syllable and morpheme onset(SM-type), IKIs for characters at the onset of syllables alone(S-type), and IKIs at pure morpheme onsets (M-type). ‘L’ specifies IKIs for characters at all other positions within a word, i.e. at all within syllable or within morpheme positions (see ‘Classification’ below). For example, in ‘c-o-n-f-o-u-n-d-e-d’ we identify: SM-IKI between ‘n-f’, S-IKI between ‘n-d’, M-IKI between ‘d-e’, all other IKIs being of type L.In the present study we are going to analyze the ‘type of boundary’ influence on IKI size, and because of the context effect we are doing this by analyzing digraph IKIs (i.e. the interval between the two key stokes for digraphs) and not just single key stroke IKIs. In order to overcome the language specific constraints mentioned above, and to obtain a substantial number cases, 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). For example, the digraph <ne> from the SM set of experiment 1 contains a SM boundary in the word <unexpected> and a L-boundary in <someone>. Likewise digraph <nd> from the S set of the same experiment contains a S-boundary in the word <handyman> and a L-boundary in <roundhouse>. Only interkey intervals for the same digraphs are compared. Due to language constraints the digraph sets used for the analyses do not contain all digraphs of the test word list (in several cases digraphs of one boundary type did not have a corresponding one in the other boundary group). Although the digraph sets were controlled for a balanced number of occurrences under the two conditions for each set, there are some digraphs with only a single context pair. Because of this restriction we do not report statistics on digraphs-as-random-effects for the different sets of all experiments. However, to indicate the consistency of our results we have included a graph for the distribution of means for digraphs over conditions for the sets of experiment 1 (see Appendix A).

Analyses for some of the experiments, however, can be done using the complete set of IKIs, as it contains the same character contexts (same word material) for the factor of interest; this is the case, for example, for the comparison between presentation modes or between delayed and non-delayed conditions.

Typing skills and digraph sets

Typing of character sequences by fingers of one hand and by alternating hands has been shown to have an influence on the timing of IKIs (Ostry, 1983; Larochelle, 1983), and this influence is dependent on typing skill (Gentner, 1983; Larochelle, 1983). Participants in our experiments showed a large range of typing skills, however, we have no way of telling how digraphs have actually been typed by a certain participant, as we did not require them to have learned typing according to the standard method. We can, nevertheless, assume that for each subject all occurrences of a specific digraph are generally typed the same way. Then, an analysis on the basis of digraph sets takes into account the various motor performances without requiring us to know how the keystroke sequences were actually executed.

Presentation modes

For methodological reasons we used visual word presentation as a reference in all experiments: with oral word presentation the stimulus is not present at once but presented successively over a period of several hundred milliseconds. This increases the uncertainty in the relation between stimulus presentation and typing onset. Consequently, we are not going to compare initial latency across visual and oral modes of presentation in cases of non-delayed typing.

Classification of sub-word units

Our study investigates three types of linguistic material: English words, German words and German based pseudo-words. An important factor for the analysis of our chronometrical data is what we call ‘type of boundary’: SM-, S-, M-, and L-type IKIs. The guidelines for the morpheme and syllable segmentation (see Appendix B) in our analyses were as follows:

1. *English words*: a) Syllable onsets were identified according to the English Pronouncing Dictionary by Jones (1997).
b) Morphological segmentation in English is complicated by the fact that there is a large number of Latin and French based elements that can be considered as morphemes from an etymological perspective, but are no longer transparent as such in present day English (cf. Katamba, 1993: 42). As we are especially interested in language production, semantic or functional transparency is used as a criterion for delimiting morphemes. In the following cases we refrain from considering the underlined elements as morphemes due to their semantic or functional intransparency, though in some cases a preceding element seems to belong to productive class of morphemes:

> abstain, affecting, confounded, conscript, container, dependence, detract, disdain, distrait, encounter, encroach, formula, immersion, immunity, incidental, mountain, observant, outskirts, perceptive, unexpected,

Our morphological segmentations can be disputed, at least in some cases, depending on one’s assumptions about writer’s knowledge of etymology. However, although productivity is not a binary variable we had to make an “either or” decision where a "more or less" might seem preferable.

2. *German words*: a) Syllable onsets are identified according to German phonotactic and graphotactic regularities and in some cases according to

morphological structure. In the case of ambisyllabic consonants that are written with the polygraphemes <double consonants, nk, ng>, we locate the syllable boundary between letter one and letter two. In the case of polygraphemes <sch, ch> segmentation follows German hyphenation rules (‘A*sche‘ [ashes], ‘Be*cher‘ [cup]).

b) Morphological segmentation in German is easier than in English, because in present day German morphology is highly productive without reliance on etymological knowledge. Of course there are some disputable cases like the relation between *wüst* [desolate] and *Wüst#e* [desert] and *lieb* [dear] and *Lieb#e* [love]. Here the letter *e* was considered as representing a morpheme, though there is a semantic difference between the adjective and the noun.

3. *Pseudo-words*: a) Syllable segmentation of pseudo-words followed German phonotactic and graphotactic regularities. There are ambiguous structures in some cases because more than one segmentation is possible in accordance with regularities of the German language; these cases have not been considered in our analyses. Ambisyllabic polygraphemes were segmented as in German words.

b) A morphological segmentation in the pseudo-words was not considered, though some prefixes and suffixes could be conceived of as being associated with German morphemes.

Other factors

Separate tests were performed to analyse the influences of word stress (experiment 1 and 2) and word frequency (experiment 1 and 5) on the size of SM- and S-type IKIs. Special subsets of the word lists in experiment 3 and 5 were constructed in order to analyse the influence of onset complexity, number of syllables, and syllable length on syllable-initial IKIs. Word frequencies and syllable frequencies for German and English words, and letter and digraph frequencies for the German word lists were recalculated from the CELEX database (Baayen et al., 1995). Letter and digraph frequencies for the English test have been taken from Mayzner & Tresselt (1965).

2. Experiment 1: Typing of English words following visual presentation

Previous studies on typewriting have not demonstrated any influence of higher linguistic units on time structures of typing words (e.g., Cooper, 1983; Ostry, 1980, 1983; Shaffer, 1978; Sternberg et al., 1978). As all these studies were conducted using the English language, it might seem possible that the results of Nottbusch et al. (1998) and Will et al. (2001) are due to differences between the German and English languages. The more complicated relation between phonology and orthography in English could be a reason why, when writing, native English speakers rely more on a lexical pathway than native speaker of German. To explore these possibilities, we performed the following study with native English speakers using the same experimental paradigm as in our previous German experiments (Will et al., 2001).

2.1. Method

2.1.1. Participants

Fourteen staff members from the School of Cultural Studies, Flinders University, South Australia, and seven staff members from UNE Armidale, NSW, Australia, participated in this experiment. All were native speakers of English, 14 were female, and 7 were male. These subjects had been selected on the basis of a pre-test, the selection criterion being that they were able to type twelve ‘pre-test’ words fluently without obvious hesitation, although no strict criteria concerning writing speed were applied.

2.1.2. Materials

48 English pluri-syllabic words with word length ranging from 7 to 10 letters served as word stimuli. The word list contained 48 word-initial syllables, 22 within-word syllables commencing with a combined syllable/morpheme (SM-type) boundary and 57 with a pure syllable (S-type) boundary. The list also included 27 morpheme (M-type) boundaries that were not at the same time syllable boundaries. Syllables were controlled for word frequency and stress pattern. The following digraph sub-sets were used for statistical analysis of IKI-types:

M-set: da, de, ma, me, ne, si, ta.
S-set: ab, ar, ct, ep, ht, id, in, it, nc, nd, nt, om, on, pt, rt, st, ul, un.
SM-set: du, ef, ne, st, th, ts.

The digraphs of each set have balanced L-type counterparts, e.g. M-set digraph <da> occurs as M-type boundary in <legend#ary> and as L-type boundary in <disd-ain>. In addition, words were grouped into high and low frequency items in order to test for word frequency effects on syllable-initial IKIs. Syllable stress was determined for all syllables and also introduced as a factor.

2.1.3. Procedure

For each test run the word list was loaded in random order by the test program. A computer screen displayed two windows, a stimulus window in the upper half of the screen and a ‘writing window’ displaying the input from the keyboard, in the lower half. At the start of each word presentation an asterisk was displayed for 800 ms at a position in the stimulus window where the first letter of the test word was to appear. Simultaneously a short beep was sounded. Next a blank stimulus window was displayed for 200 ms before the test word was displayed for 400 ms. Subjects were instructed to type the word immediately and after pressing the <return>-key they activated the next presentation that commenced after a delay of 1 sec.

Subjects were instructed to type as quickly as was conveniently possible, and, in the case of mistyping, not to correct the mistake but to continue with the next trial by striking the <return> key. As we are not concerned with error analysis here, measurements for all mistyped words as well as outliers (> 5* IQR (interquartile range): ILs > 2500 ms and IKIs > 1500 ms) were excluded from analysis. Each subject had completed a pre-test with a set of 12 words that were not part of the main test list. After a break and, if necessary, repeated instructions the main test was performed.

2.2. Results

The average interkey time (without initial latencies) was 255 ms and ranged from 136 to 459 ms. This corresponds to an average writing speed of 47 words/min. Measurements were split up into two speed groups and averaged over subjects for each group. The average writing speed was 32 words/min. for group A and 55 words/min. for group B.

For both speed groups analysis of variance of the respective digraph sets revealed highly significant differences between L and S, L and SM, but not between L- and M-type IKIs (for an example see Fig. 1). ANOVA for the M-digraph set shows no significant differences between L- and M-type IKIs (fig. 1c) (Speed group A: $F(1, 28) = 0.74$, $p = 0.395$; speed group B: $F(1, 28) = 0.41$, $p = 0.529$). There were, however, significant differences between L- and S-type IKIs of the S-digraph set (Speed group A: $F(1, 72) = 6.18$, $p = 0.015$; speed group B: $F(1, 72) = 7.96$, $p = 0.0062$) (fig. 1b) as well as for the L- and SM-type of the SM-digraph set (Speed group A: $F(1, 15) = 9.45$, $p = 0.0077$; speed group B: $F(1, 15) = 12.40$, $p = 0.0031$) (fig. 1a).

Fig. 1.

In general, the absolute size of L-, S-, and SM-type IKIs as well as their relative differences seem to be inversely related to typing speed. For speed group A (slow) mean differences are: L/S 33 ms, L/SM 143 ms, S/SM

110 ms, and for speed group B (fast) the mean differences are: L/S 22 ms, L/SM 82 ms, S/SM 60 ms.

Further analysis indicated a significant word frequency effect on SM-type IKIs for the fast typists (group B: $F(1, 20) = 5.17$, $p = 0.0342$) but not for the slow typists (group A: $F(1, 20) = 1.07$, $p = 0.3131$). Although the mean differences between SM-type IKIs of high and low frequency words are of comparable size in both speed groups (slow group: 41.7 ms, fast group: 56.8 ms) it does not reach significance level for the slow typists due to the larger variance within this group. There was no word frequency effect on S-type IKIs ($F < 1$ for both speed groups). These results resemble those reported by Will et al. (2001) for German.

Syllable stress was not found to have an influence on either SM- or S-type IKIs ($F < 1$ for both tests and both speed groups)

It should not remain unnoticed, that for 11 (13.9% out of 79) non-initial syllables IKIs at the syllable boundaries were not augmented with respect to the immediately preceding IKIs. 10 of these were IKIs at S-boundaries (out of 49; that is 20.4%) whereas only 1 (4.5% out of 22) concerned SM-boundaries. There does not seem to exist a single factor explaining these ‘non-delayed’ typings of syllable boundaries. Some factors that could be identified are: Character keys in extreme position on the keyboard and/or with low frequency, leading to extended IKIs that might prevent the following IKI to be a local maximum, and character repetitions, in which the IKI leading to the repeated character are always shorter than the previous one. Interestingly, the one ‘non-delayed’ case of an SM-type IKI is produced by such a character doubling.

As in our previous study with German subjects (Will et al., 2001), we are unable to confirm Ostry’s (1983) finding of a general slowing of typing speed (increase in IKI duration) at mid-word level. We suspect that Ostry’s interkey time functions may arise from the fact that he averaged over words in which syllable boundaries coincided with mid-word level (see Will et al., 2001 for a discussion). A general breakup of the typing sequence of a word at mid word level, independent of syllabic word composition could not be confirmed (see however the discussion of sub syllabic units in the General Discussion section). In our experiment the increased IKIs at SM- and S-boundaries are not generally preceded by a rise in the interkey time for the final characters of the preceding syllable (Fig. 2). Therefore we feel justified in saying that planning and/or initiation of a syllable does not seem to cause a gradual decrease in the typing speed of the preceding syllable; it is only manifest at the transition from one unit to the next, i.e. at the boundary itself.

Fig. 2.

2.3 Discussion

Results can be summarized as follows: Interkey intervals were found to be significantly larger for the first character of syllables (S- and SM-type IKIs) than for within-syllable characters (L- and M-type IKIs). The two types of augmented IKIs, those at syllable (S-type) and at combined syllable-morpheme (SM-type) boundaries are readily distinguishable by size as well as by factors influencing them: SM-type IKIs are considerably larger than S-type IKIs. Word frequencies were found to influence SM-type but not S-type IKIs. In the present experiment morphemes do not seem to influence the timing of typing sequences as there were no significant differences between M-type and ‘within-morpheme’ IKIs. It can be argued that the fact that morphemes do not figure as units in the time structure of typing is conditioned by the experimental design in which active word construction is not involved (see, however, this point in the general discussion).

Words are obviously not typed in one go but as a sequence of sub-word units. This means that input to the motor system does not consist of fully specified words, but of sub-word units that receive their final specification the moment they are transformed into typing movements.

Interestingly both, SM- as well as S-type units are related to the syllabic structure of words. Many psycholinguistic studies have advanced evidence on syllables as units of language processing (e.g., Carreiras et al., 1993; Ferrand et al., 1996; Mehler et al., 1981; Roelofs & Meyer, 1998; Santiago et al., 2000; Shattuck-Hufnagel, 1979; Sternberg et al., 1978; Itô et al., 1995, Fujimura, 2000). Whereas most of those studies concern spoken language, results presented above as well as those reported by Will et al. (2001) are evidence for the psychological reality of syllabic (S-type) units in typewriting. The morpho-syllabic (SM-type) units we have been able to identify have, to our knowledge, not been described previously. Although in the present study these units have been identified by their left boundary (i.e. joined start of a syllable and a morpheme) there is evidence that we are, in fact, dealing here with units larger than syllables and not just with a special type of interkey intervals: Will et al. (2001) have shown that SM-type IKIs are larger when followed by S-type IKIs than by SM-type IKIs, i.e. their length reflects immediately following syllabic units. Obviously, these SM-units are to be located between the syllable and the word level. SM-units can comprise one or more syllables; they can be identical with words, if these consist of lexical or root morphemes, or with parts of compound words. In the majority of cases from our material SM-boundaries are onsets of free or lexical morphemes, which in English and German always are onsets of new syllables. In several cases these lexical morphemes are affixed with bound morphemes before the words ends or the next lexical morpheme starts (i.e. before the next SM-boundary). In other cases SM-boundaries are onsets of bound morphemes: e.g. ly in light+ly. Nottbusch et al. (1998) have indicated that SM-type IKIs are influenced by the type of morpheme commencing with them, however, further studies are needed to elucidate this relationship.

The information contained in our chronometrical data relates to at least four different hierarchical levels: 1) word level: initial latencies (IL) are influenced by general word features, e.g. the number of syllables (Will et al., 2001). 2) SM-level: SM-type IKIs are influenced by e.g. word frequencies and the number of syllables contained in the SM-unit. 3) syllable level: S-type IKIs are influenced by e.g. syllable length and onset complexity (see experiment 3). 4) sub-syllabic (grapheme) level: within-syllable IKIs are influenced by syllable frequencies and position within the syllable (Ostry, 1983; Will et al., 2001). Concerning the locus of origin of the different delay types it can be argued that the dependency of SM-type IKIs on word frequencies most likely indicates an influence of lexical (wordform) units or sub-units: the word frequency effect was discovered by Oldfield and Wingfield (1965) and evidence has been forwarded that access to the wordform lexicon is the major and probably unique locus of the word frequency effect (Jescheniak and Levelt , 1994; Caramazza et al., 2001). As for the other delay types we can only say, at this stage, that S-type IKIs do not show a word frequency effect, and S- and SM-units seem to be generated along two different pathways of the language processing hierarchy. However, experiment 3, 4, and 5 have been designed to elucidate the locus of origin of these other delay types within the processing hierarchy.

Tentatively, the above results can be interpreted in terms of 'dual-route' models for spelling originating from Morton's (1980) extended logogen model (see also: Ellis, 1982). Originally these two routes were considered alternatives, the 'lexical route' being used for exception words (words in which the correspondences between letter and phoneme sequences is arbitrary) and the sublexical or extralexical route for regular words (regular correspondence between letters and phonemes) and pseudo-words. This distinction is essentially based on clinical manifestations of selective impairments of these two reading procedures in phonological dyslexic and surface dyslexic patients. However, there are new theoretical considerations as well as growing experimental evidence (e.g., Monsell et al., 1992; Zorzi et al., 1998), suggesting that there might be cooperation between the two routes with context dependent variable weighting between them. Our results also seem to indicate a combined use of lexical and sublexical pathways. In case of exclusively lexical pathways, as for example suggested by Glushko (1979), we should expect S-type IKIs to be influenced by word frequencies. This, however, was not the case in the present experiment.

3. Experiment 2: Typing of German words following oral presentation

The following experiment was performed to test whether increased S- and SM-type IKIs are also present in typing following oral word presentation. Furthermore, as there are indications that lexical processes, i.e. access of wordform lexica, might be involved, a comparison between oral and visual word presentation might also give us some clues about whether phonological wordforms are obligatorily accessed (phonological mediation hypothesis) in the case of visual word presentation.

Research on reading aloud has been dominated in the last two decades by the idea that two independent routes govern lexical access, a direct visual and a mediated, phonological pathway (Coltheart et al., 1993). There is, however some controversy about status and features of the assembled phonological access route in reading. The two principal positions are: a) The phonological route is slower than the visual one and, if used at all, is too slow to influence reading of familiar words in the normal time course of word identification (Coltheart, 1980; Seidenberg & McClelland, 1989; Jared & Seidenberg, 1991); b) prelexical assembled phonology is an early and non-optional source of constraints on word recognition (Van Orden et al., 1988; Lukatela et al., 1993). It can be argued that reading aloud and typing visually presented words both make use of the same lexical access routes; the two tasks probably do not involve different processes prior to the level of lexical output.

Van Galen (1991) has proposed a model for handwriting that generally assumes a full specification of phonological words prior to the generation of corresponding graphemic forms. As discussed above, our results for typing are incompatible with the assumption of a fully specified word at pre-motor levels. However, it might seem possible that sub-word units of SM- or S-type instead of complete words are processed as proposed by the van Galen model.

In any case, if phonological mediation is a necessary condition of lexical access, one would expect either equal time intervals to initiate typing for both, visual and acoustical presentation modes (if the time necessary for phonological wordform activation via assembled phonology is about the same in both modes), or longer intervals in the visual than in the oral mode because additional processing stages are involved. For visual word presentation the phonological wordform lexicon might become activated via the grapheme-phoneme conversion mechanism of the assembled or computed phonology route and in turn activate the graphemic output, whereas this grapheme-phoneme conversion mechanism would not be activated in the case of oral word presentation. Unfortunately, our experimental design does not allow for a direct comparison of word initial latencies in the two presentation modes (see introduction). However, as words are obviously processed as a sequence of syllabic sub-units in typewriting, it seems possible that the conversion mechanism also proceeds along such sub-word units. Therefore we are also going to compare S- and SM-type IKIs of the present experiment with those of an identical (word list, subjects) experiment reported by Will et al. (2001) in which words were presented visually.

3.1. Method

3.1.1. Participants

Twenty-three linguistic students at the University of Osnabrück participated as subjects on a voluntary basis. All were native speakers of German, 12 were female, and 11 were male. These subjects had been selected on the basis of a pre-test, the selection criterion being that they were able to type a series of twelve test words fluently without obvious hesitation. No strict criterion was applied concerning writing speed.

3.1.2. Materials

75 German words with word length ranging from 3 to 11 letters, containing from 1 up to 4 syllables, served as word stimuli. The material contained 168 syllables, comprising 75 ILs, 49 SM- and 46 S-type boundaries, and 349 characters that were not associated with any of these boundaries. Syllables were controlled for word frequency and stress.

The digraph sub-sets considered in the analysis were as follows:

S-set: ab, hn, hr, nd, nt, ot, rn, rt, st, uf.

SM-set: el, nd, st, ta.

Due to a design error in the word list of this experiment we do not consider M-type IKIs here(Out of 32 M-type IKIs 26 are ‘e’s and suffer from a serial position effect; see Will et al., 2001).

The 75 German words for this experiment were read aloud, digitally recorded, and stored as separate sound files onto a computer hard disk.

3.1.3. Procedure

For technical reasons, the replay sequence of sound files (spoken words) was the same for each participant. One second after a short beep a word was replayed through the speaker system of the computer. Subjects had been asked to respond immediately and, following completion of typing, to activate the next trial by hitting the <return> key. Selection of participants and instructions were the same as in the previous experiment.

Outliers (= 5*IQR: ILs > 2000 ms; IKIs > 1500 ms) and words with typing errors are not considered in the present analysis.

Due to the specific experimental design, initial latencies of this experiment and of visual word presentation experiments cannot be directly compared (see: Methodological considerations).

3.2. Results

As in Experiment 1, measurements were split up into two groups according to subjects' typing speed (group A: 34 words/min. and group B: 58 words/min.) and averaged over subjects.

ANOVA shows highly significant differences in mean IKI size between L- and S-type IKIs (group A (slow): $F(1, 64) = 6.38$, $p = 0.0140$; group B (fast): $F(1, 64) = 9.40$, $p = 0.0032$) as well as between L- and SM-type IKIs (group A (slow) $F(1, 24) = 21.08$, $p = 0.0001$; group B (fast) $F(1, 24) = 116.07$, $p < 0.0001$).

As in the previous experiment, the different IKI-types have different duration and are influenced by different factors. Again the relative difference between IKI-types depends on typing speed. Mean difference between L- and S-type IKIs is 48.7 ms for the slow and 33.1 ms for the fast typists. Mean difference between L- and SM-type IKIs is 173.1 ms for the slow and 111.4 ms for the fast typists. SM-type IKIs are affected by word frequencies for fast typists (group A (slow): $F(1, 46) = 0.79$, $p = 0.3793$; group B (fast): $F(1, 46) = 4.86$, $p = 0.0325$) while S-type IKIs are not ($F < 1$ for both speed groups). The mean SM-IKI difference between high and low frequency words is of comparable size in both speed groups (group A: 47.1 ms; group B: 50.1 ms) but does not reach significance level in the slow typist due to the larger variance in the data of this speed group.

As in experiment 1, no slowing before the local maxima at syllable boundaries was found. In both speed groups, the mean IKI for the character to the left of a syllable boundary is smaller than that for the preceding one.

The difference between these two IKIs is not statistically significant, both are, however, significantly ($p < 0.0001$ for both speed groups) smaller than the following S- or SM-type IKI. Local IKI peaks at syllable boundaries are not generally accompanied by a gradual augmentation of the IKIs for the two immediately preceding characters. Syllable stress was not found to excert and influence on the size of S and SM-type IKIs.

With oral word presentation there were nine syllable boundaries without augmented IKIs with respect to the immediately preceding IKI. Eight of these were IKIs at S-boundaries (out of 44; that is 18.2%) whereas only 1 out of 49 SM-boundaries (2%) were 'non-delayed'. As in Experiment 1 there was no single factor to explain these 'non-delayed' typings. They are influenced by word length, word frequency, syllable frequency, but not by syllable length, and the one 'non-delayed' SM-boundary was again caused by character repetition across the boundary, a condition that always produced 'non-delayed' S- or SM-type IKIs.

Comparison between written word and oral presentation test

In the following we compare results of the present experiment with those from the experiment with visual word presentation reported in Will et al. (2001). An example for both presentation modes is given in Fig. 3.

Fig. 3.

There were no significant differences in L- or S-type IKIs between the two presentation modes ($F = 1.1$ for L-type IKIs and $F < 1$ for S-type IKIs). However, there is an effect of presentation mode on the SM-type IKIs that is significant for the fast typists (see figure 4) and approaches significance for the slow typists (fast group: $F(1, 94) = 4.65$, $p < 0.0336$; slow group: $F(1, 94) = 3.72$, $p < 0.0569$). The mean difference between modes is similar in both speed groups (30.9 ms for fast and 31.5 for slow typists).

Fig. 4.

3.3 Discussion

The results of the second experiment indicate that segmentation of IKI sequences along S- and SM-boundaries in typewriting is not dependent on a specific mode of word presentation. Augmented IKIs at syllable and combined syllable/morpheme boundaries occur under visual as well as under oral word presentation. The augmented IKIs are of similar size and are influenced by the same factors in both experimental conditions. However, comparing IKI-types between presentation modes there is a noticeable difference for SM-type IKIs: they are longer for oral than for visual word presentation. According to the phonological mediation hypothesis, access to graphemic word forms is only possible via prior activation of phonological word forms. If this were indeed the case, and under the provision that SM-type IKIs do reflect access to the wordform lexicon – as indicated by the word frequency effect – then SM-delays should be longer following visual word than oral word presentation. Another possibility would be – under the unlikely assumption that visual word presentation leads to an activation of (only) the phonological word form with the same delay as oral word presentation – SM-delays might be the same in both modi. Our results, however, show that SM-type IKIs were considerably (average: 35 ms) and significantly longer in the oral than in the visual word presentation. These differences probably have something to do with the different accessibilities of the graphemic code in the two presentation modes. With written word presentation this code is either directly available or more easily accessible due to input information, whereas no grapheme related information is directly available in the case of oral word presentations. We take our results to suggest that each time the graphemic wordform (graphemic code) is accessed during typing of a word there is an additional process involved in the case of oral word presentation: the activation of the graphemic code on the basis of the available phonological information. Furthermore, for words with more than one SM-unit, our data suggest that the activation of graphemic wordforms is not immediately complete or completed at the beginning of typing. Rather, this phonologically mediated activation appears to be performed ‘in parallel’ to typing and proceeds in lexical chunks corresponding to our SM-units. This seems straightforward if we consider words consisting of two lexical or root morphemes. For instance if <handyman> or <greyhound> are presented orally this leads to activation of phonological word forms or word form sub-units <handy> and <man> or <grey> and <hound> respectively, which then lead to activation of the corresponding graphemic forms in coordination with typing of the respective units.

It is a moot point whether visual word presentation leads to an activation of only the graphemic word form or, quasi simultaneously, to an activation of both the graphemic and phonological word form. In any case, our chronometrical data do not seem to be compatible with models, like that of van Galen (1991), in which graphemic word forms can only be accessed via prior activation and specification of corresponding phonological word forms. There are several reports of clinical cases indicating that orthographic information is not obligatorily mediated by phonology (some of the more recent reports: Blanken, 1990; Caramazza & Hillis, 1990; Marini & Blanken, 1996; Miceli et al., 1997; Rapp et al., 1997). Despite a careful evaluation and presentation of these cases, one objection could still be raised: they are dealing with impaired and hence modified cases of language processing. However, the evidence we have given in the present study also points towards an independent accessibility of orthographic information – but this time in un-impaired, ‘normal’ subjects.

4. Experiment 3: Comparison of typing picture names and visually presented words (German)

The first two experiments have shown that the representation of syllabic units in the time structure of typewriting is a phenomenon neither limited to one language nor restricted to a specific form of word presentation. The question remains, at what level of the processing hierarchy are these ‘delays’ generated, on the ‘perception’ or on the ‘production’ side. It is conceivable that they originate from information that can be derived from both oral and visual word stimuli. Contemporary models of speech and language processing account for such possibilities by proposing connections between auditory and visual input buffers and orthographic (and phonological) output buffers. Furthermore, evidence on the syllable as language processing unit is still stronger in speech perception and reading tasks (e.g., Carreiras et al., 1993; Mehler et al., 1981) than in speech production (e.g., Sternberg et al., 1978; Ferrand et al., 1996; Santiago et al., 2000; Sevald et al., 1995). In the following experiment we are going to test whether delays (augmented IKIs) at syllable and combined syllable/morpheme boundaries originate only from information extracted from the stimulus input (pre-lexical) or whether they can also be generated at a lexical or post-lexical level, independent of the actual input information. The test was performed by comparing word typing in response to visual word presentations and a picture naming procedure. If there are no delays at S- and SM-boundaries under the latter condition, then these delays can be considered to originate from pre-lexical input processing. However, if, on the contrary, delays are also present for the picture naming procedure, than we can reasonably assume that in this case they have been generated at either lexical or post-lexical levels, because in picture naming the input contains no information about syllable and morpheme structure. This test can be performed as a direct comparison of all IKIs in the two presentation modes because the lists of typed words are identical.

We also address the question, whether in German there are increased IKIs at morpheme boundaries (M-type) – a question we were unable to attack with the material of the previous experiment

A third question addressed in this experiment is that of the influence of onset complexity on the size of IKIs at syllable boundaries. Santiago et al. (2000) have shown that in (oral) picture naming the initial latency (naming latency) is influenced by the complexity of the onset of the first syllable, being longer for two onset consonants than for one. As typing appears to proceed in syllabic units we wanted to know whether onset complexity influences syllable-initial IKIs (i.e. S- and SM-type IKIs).also in within-word syllables. A positive result would strengthen the argument that the S- and SM-units of the present study are indeed structured syllabic sub-word units.

4.1 Method

4.1.1. Participants

Twenty-seven linguistic students at the University of Osnabrück participated in the experiment for course credits. All were native speakers of German, 19 were female, and 8 were male.

4.1.2. Materials

36 black-and-white line drawings of objects whose names contained two or more syllables were selected from Snodgrass and Vanderwart (1980), digitized, edited, and saved as pict files. The German names of the depicted objects (from: Genzel et al., 1995) were saved as a text file for the visual word presentation.

4.1.3. Procedure

Technical procedures for stimulus presentation were exactly the same as in the first experiments, except that the text window for visual presentation was replaced by a graphics window in the picture naming task.
For each of the two test series every subject had run a pre-test with a set of 10 stimuli that were not contained in the main test; following a break and, if necessary, repeated instructions the main test was performed.
Outliers (ILs > 2500 ms; IKIs > 1500 ms) and words with typing errors are not considered in the following analysis.

4.2 Results

The average interkey interval (without initial latencies) was 306 ms and ranged from 164 to 414 ms. This corresponds to an average writing speed of 39.2 words/min. with a range from 73.2 to 29.0 words/min. Measurements were split up into two speed groups and averaged over subjects for each group. The average writing speed was 33 words/min. for group A (slow) and 47 words/min. for group B (fast).

If we compare L- and M-type IKIs in the picture naming condition there are no significant differences (group A (slow): $F(1, 21) = 0.37$, $p = 0.5490$; group B (fast) $F(1, 21) = 0.01$, $p = 0.9239$). Likewise, there are also no differences between these two IKI-types under visual word presentation (group A (slow): $F(1, 21) = 0.77$, $p = 0.3910$; group B (fast) $F(1, 21) = 0.15$, $p = 0.7036$). The results are in accordance with those from experiment 1 for English speaking subjects and, for the remainder of the present study, we are no longer considering M-type IKIs separately from L-type IKIs.

Comparison between written word and picture presentation test

The initial latencies for the picture naming are considerably longer than for visual word presentation (slow group: $F(1, 70) = 81.57$, $p < 0.0001$; fast group: $F(1, 70) = 79.43$, $p < 0.0001$). The differences reflect the additional load in the picture-naming task needed for semantic identification of the respective pictures (see Fig. 5). The mean difference between the two modes is 376.2 ms for the slow and 347.0 ms for the fast typists.

IKI comparison across presentation modes indicates significant differences for the fast ($F(1, 414) = 3.89$, $p = 0.0493$) but not for the slow typists ($F(1, 414) = 0.42$, $p = 0.5175$). The average difference between the two modes is 18.0 ms for the fast and 9.3 ms for the slow typists. If we compare IKI-types separately across modes there are no significant differences for the slow typists ($F < 0$ for all three types). An example of the IKI sequence for one word in both presentation modes is given in fig.5.

Fig. 5.

For the fast typists modal differences approach significance for L-type IKIs ($F(1, 278) = 2.93$, $p = 0.0882$), but not for S-type IKIs ($F(1, 82) = 0.62$, $p = 0.4343$) or SM-type IKIs ($F(1, 50) = 1.26$, $p = 0.2671$). The fact that modal differences are nearly the same for within-syllable IKIs (L-type) and for IKIs at syllable boundaries (for slow typists the mean difference is 7.8 ms for L-type IKIs and 6.0 ms for S-type IKIs and for fast typists it is 17.0 ms for L-type IKIs and 15.7 ms for S-type IKIs) suggests that all IKI-types are affected in a similar fashion. That means, although picture naming puts an extra load on all IKI-types, there are augmented S- and SM-type IKIs as with visual word presentation.

Fig. 6.

Onset complexity of within-word syllables was found to have a significant effect on IKIs at syllable boundaries (S- as well as SM-type IKIs). Although syllable-initial IKIs are also influenced by syllable length (number of characters; see Will et al., 2001), there was no significant interaction between syllable length and onset complexity ($p > 0.5$). ANOVA was therefore performed on all within-word syllables. For picture naming we obtained $F(2, 68) = 5.90$, $p = 0.0043$ for slow and $F(2, 68) = 3.40$, $p = 0.0392$ for fast typists and with visual word presentation we found $F(2, 68) = 4.62$, $p = 0.0132$ for slow and $F(2, 68) = 4.23$, $p = 0.0186$ for fast typists.

Post-hoc tests (Scheffé) showed significant differences between syllables with one- and two-character onsets ($p < 0.04$ for all four tests). Differences between two- and three-character onsets approached significance (p between 0.064 and 0.052). Syllable-initial IKIs are larger for syllables with two character onsets than with one-character onsets. Interestingly, initial IKIs for syllables with one or three onset characters have comparable size.

4.3 Discussion

Apart from the considerable additional load on the ILs due to processes related to semantic identification and subsequent lexical activation, the picture naming procedure also seems to exert a small influence on the typing speed, i.e. all IKI-types are slightly enlarged, though this only approaches significance in fast typists. The question of what exactly these influences are and from where they originate, however, needs further research. However, the fact that both, augmented S- and SM-type IKIs as well as the effect of onset complexity, were observed in the modified picture naming procedure, where all the information necessary for writing must be obtained via lexical activation, indicates that they are attributable to the production rather than perception side. These effects seem to be generated at lexical and/or post-lexical levels during retrieval and sequential activation processes and can obviously be generated independently of any phonological or graphemic information derived directly from orally or visually presented word stimuli.

In both, picture naming and visual word presentation, there were no significant differences between L- and M-type IKIs. The finding that pure morpheme boundaries do not appear to exert an influence on the size of the interkey intervals in typing of both English and German words should, however, be interpreted within the framework of our experimental design. Orliaguet and Boë (1993), for example, have shown that the application of grammatical rules to stimulus words does influence initial latencies as well as production time of written words, but to our knowledge there are no reports about timing effects at morpheme boundaries.

The influence of onset complexity on syllable-initial IKIs is a further indication that S-and SM-units are processed as syllabic units in typewriting. Will et al. (2001) have found that initial latencies were longer if words commenced with consonant characters (onset) than if they started with a vowel characters (nucleus), but there was no effect of nucleus or coda complexity. Both these results are compatible with those reported by Santiago et al. (2000) for (oral) picture naming and provide further support for the psychological reality and hierarchical organization of syllabic structures. Whereas Santiago et al. (2000) reported an effect of onset complexity only for initial latencies in oral picture naming, our typing experiment shows that the effect is detectable not only for the first but for all syllables of a word. These findings suggest that planning and/or preparation of sub-word units in typing does not occur while previous units are being typed but rather when their typing has been completed, i.e. at the transition between sub-word units.

The finding that three-character onsets have about the same effect on syllable-initial IKIs as one-character onsets seems to be at variance with predictions on the basis of McKay's (1987) node structure theory. According to this theory, syllable-initial IKIs for three-character onsets should have the same size as those for two-character onsets because it takes the same time or the same number of sequential decisions to activate the first segment (the left-most, bottom-most nodes in the hierarchy of 'content nodes') in both cases. We suggest the following explanation: all three-character onsets in our experiment consist of the same three-character combination <sch> in syllables like <sche>, <schen>, <schuh>. In German this combination corresponds to the unitary phoneme [Σ] and it might be possible that – in analogy to the corresponding phoneme – this trigraph is treated as a unit in the activation process of the node hierarchy and therefore requires the same time to be activated as a one-character onset. If this can be shown to hold in an independent experiment, it would indeed open an interesting new perspective on nature and genesis of the graphemic code (on polygraphemes as sub-syllabic units see Weingarten, 2001).

5. Experiment 4: Typing of visually presented pronounceable (German) pseudo-words

The previous experiment suggested that delays at SM- and S-type IKIs are produced at lexical or post-lexical level. The dependency on word frequency indicates lexical influences on SM-type IKIs. In order to test whether, as indicated by experiments 1 and 2, S-type segmentation can also occur without the involvement of word form activation and/or independently of lexically derived information we performed the following experiment with pseudo-words.

5.1 Method

5.1.1. Participants

Nine students and staff members from the University of Osnabrück participated in this experiment. All were native speakers of German, four were female, and five were male.

5.1.2. Materials

22 pronounceable pseudo-words were constructed that, according to German phonology, give clear preference to an unambiguous syllable structure (like ‘au-re-lu’, ‘mie-be’). Some pseudo-words contained ambisyllabic elements that were segmented like in the previous experiments (e.g. ‘bram-mer). The list comprised wordlengths of 5 to 13 characters; the number of syllables per word was either 2 or 3. The complete word list contained 57 syllables (with syllable lengths from 1 to 6 characters).

5.1.3. Procedure

Technical procedures were exactly the same as in the first experiment. Subjects were instructed to type as quick as conveniently possible, and, in case of mistyping, not to correct the mistake but to continue with the next trial instead by hitting the <return> key. Outliers (ILs > 2500 ms and IKIs > 1500 ms) and mistyped words are not evaluated in this study.

Each subject had run a pre-test trial with 8 pseudo-words that were not part of the main test.

5.2. Results

The average interkey interval was 262 ms and ranged from 198 to 326 ms, corresponding to an average writing speed of 45.8 words/min. with a range from 60.6 to 36.8 words/min. IKIs were averaged over subjects and classified as either S-type (at syllable boundaries) or L-type (at within syllable positions). As can be seen from Fig. 7 the IKI sequences for pseudo-words indicates segmentation according to syllable boundaries similar to that for normal words.

Fig. 7.

Analysis of variance for the IKIs of the digraph set, shows a significant difference between IKIs at syllable boundaries (S-type) and at within syllable position (L-type): $F(1, 23) = 6.58$, $p = 0.0173$) with a mean difference of 53.0 ms between S- and L-type IKIs.

5.3. Discussion

The results show that pseudo-words are typed with S-type segmentations comparable to those of normal language words. As pseudo-words are considered to have no lexical representations this type of segmentation cannot be derived from activated word form entries. Also, an influence of a phoneme-grapheme conversion mechanism, activated directly from auditory input, can be excluded as we are dealing with visual word presentation here. Obviously, visually presented pseudo-words do not come with S-type labels attached to them and lexical help does not exist – these pseudo-words were probably seen for the first time during this experiment. In accordance with the suggestions of Butterworth (1992) we shall assume that the process of reading pseudo-words (word-form perception) generates information in the same or similar format as those of the word-form lexicon, i.e. information about syllable structure and a list of segments that can be 'spelled out' and assembled by subsequent relevant subsystems. Results of experiments 1 to 4 indicate that this 'spelling out' and reassembling leading to S-segmentation takes place at sub- or post-lexical level: S-type IKIs occur in pseudowords and S-type segmentation of comparable order was observed following visual and oral word presentation as well as in the picture naming experiment. Although all necessary information is derived from activated word-forms in the latter case, Nottbusch and Weingarten (2000) have recently demonstrated that S-type IKIs are not influenced by word frequencies in picture naming and visual word presentation experiments. These findings strongly favor an origin at post lexical level for the S-type segmentation.

6. Experiment 5: Comparison of delayed-typing of orally and visually presented words with undelayed typing

In the following experiment we are going to compare the pattern of key timing in cases of immediate responses with that of delayed typing. If under this latter condition, we obtain a different or no time segmentation in relation to linguistic boundaries, this might explain, why segmentations according to SM- and S-type IKIs were not identified in previous research applying a delayed response paradigm. More important, however, such a comparison might allow for a detection and characterization of memory buffers, especially the working of a possible motor system input buffer under these two response conditions.

Ostry (1983) has shown that the length of preparation time before typing had an influence on the initial latency. However, in his experiments this influence did not seem to extend beyond the first character of a word. Ostry (1983) tested typing with delays of 0, 50, 100, 200, 400, and 800 ms and reported a decrease of the average initial latency from 615 ms at 0 ms response delay to a value of 310 ms at 800 ms response delay. As it was not clear from his report whether the initial latencies reached a minimum at 800 ms or not, we performed a separate test with delays from 1000 to 2400 ms (in steps of 200 ms) to determine the minimum initial latencies in both visual and aural word presentation. Latencies for visual presentation had their minimum at 1800 ms and those for oral presentation at 2000 ms. As the increase of the former, from 1800 to 2000 ms , was larger than the respective decrease of the latter, we chose 1800 ms as the delay for the following experiment.

6.1 Method

6.1.1. Participants

21 students (13 female/8 male) from the University of Osnabrück participated in this experiment. All were native speakers of German; none had participated in any of the previous experiments.

6.1.2. Stimuli

108 nouns with word lengths ranging from 4 to 16 letters/word and containing from 1 to 4 syllables were used as stimuli in this experiment. The list also contained 21 two-syllable words with 4 characters per syllable and 1 to 3 onset characters for the test of onset complexity. The words were saved as a text file for the visual presentation. For oral presentation, object

names were read aloud, digitally recorded and stored as separate sound files as in experiment 2.

As all three test conditions contain the same word list, statistical analysis can proceed by direct comparison of the respective IKI-types. However, to avoid confounds due to different character contexts, the test for a word frequency effect on SM-type IKIs is based on the following digraph-set: do, ed, er, es, ie, rb, rf, rz, st, te.

6.1.3. Procedure

Technical procedures for stimulus presentation were exactly the same as in the first two experiments. For visual word presentation an asterisk was displayed for 800 ms at a position in the stimulus window where the first letter of the test word was to appear. Simultaneously a short beep was sounded. Following 200 ms of blank stimulus window the test word was displayed for 400 ms. For the un-delayed trials participants were instructed to start typing immediately. For the delayed visual presentation, another beep was sounded 1800 ms after the word display and participants were instructed to start typing with the second beep. For oral word presentation spoken words were replayed through the speaker system of the computer 1000 ms after an initial beep. 1800 ms after the stimulus another beep was sounded and subjects were instructed to start typing immediately at the second beep. By hitting the <return>-key they activated the next presentation that commenced after a delay of 1 sec in all trials. The sequence of word presentation/typing modes were: visual presentation and undelayed typing (vi-u), visual presentation and delayed typing (vi-d), oral presentation and delayed typing (or-d). Instructions and pre-trial training were given as in the previous experiments. Outliers (ILs > 2500 ms and IKIs > 1500 ms) and mistyped words are not evaluated in this study.

6.2. Results

The average interkey interval was 354 ms and ranged from 224 to 458 ms. This corresponds to an average writing speed of 33.9 words/min. with a range from 53.6 to 26.2 words/min. Due to the comparatively small range, subjects were not split into different speed groups.

Comparing the three presentation/typing modes across the boundaries IL, L, S, and SM, there is only an effect of presentation mode on initial latencies ($F(2, 321) = 1565.34$, $p < 0.0001$) but not on any of the IKI-types (F values < 1 for all IKI-types). Post hoc tests for the ILs show significant differences between the delayed and the undelayed modes (mean diff. vi-u/or-d: 611.3 and vi-u/vi-d: 623.0 ms, $p < 0.0001$ for both) but not between the delayed modes (mean diff. or-d/vi-d: 11.7 ms, $p = 0.6545$).

Fig. 8.

Differences between boundary types are again significant ($p < 0.01$ for all comparisons), i.e. the increased IKIs at S- and SM-boundaries are still present in the case of delayed typing for visual as well as for oral word presentation. Word frequency still has a significant effect on SM-type IKIs in both visual ($F(1, 63) = 7.14$, $p = 0.0096$) and oral delayed typing ($F(1, 63) = 8.14$, $p = 0.0059$), but modal differences for SM-type IKIs (see experiment 2) are no longer significant: $F(1, 128) = 1.02$, $p < 0.3023$. Nevertheless, there still seems to be a slight but consistent (not significant) time advantage for typing with visual word presentation. The mean differences between visual and oral word presentation are 2.6 ms for L-type IKIs, 10.5 ms for S-type IKIs, and 16.9 ms for SM-type IKIs.

The results of the present experiment are in accordance with Ostry's (1983) finding that delays ('preparation time') between stimulus presentation and typing only affect the timing of the first character. Furthermore, our material indicates that due to the preparation time the load on the first character of a syllable due to number of syllables per word, number of characters per syllable and onset complexity, vanishes or is considerably reduced for the first syllable of a word but not for the following syllables (see Fig. 9 – 11).

Initial latencies have already been shown to be influenced by the number of syllables per word (Santiago et al., 2000; Sternberg et al., 1978; Will et al., 2001). The word material for the present experiment included 3 series of 1 to 4 syllable words with syllable lengths of 4 characters (i.e. word composition: 4, 44, 444, and 4444 characters. As can be seen from Fig. 9, increasing the number of syllables notably augments initial latencies in un-delayed typing. However, except for a slight increase for the 4444 words (not significant), there is no additional load on ILs in delayed typing. Similar results were obtained with syllable lengths of 2 characters and word compositions 22, 222, and 2222.

Fig. 9.

The effect of syllable length on the first character IKIs is somewhat difficult to compare between the first and the following syllables of words due to unavoidable context differences. The closest we could get was to compare bi-syllabic words in which either the first or the second syllable varied in length whereas the other syllable was of constant length. Our word list contained bi-syllabic words, in which one syllable varied in length from 2 to 5 characters and the other contained 3 characters, i.e. word composition was 23, 33, 43, and 53 for the first and 32, 33, 34, and 35 for the second series.

Fig. 10.

Fig. 10 shows that IKIs for the first character of within-word syllables increase up to a syllable length of 4 characters and drop in size at lengths of 5 characters. In contrast, ILs (=IKIs for the first character of word initial syllables) remain constant for syllable lengths of 2 to 4 characters. However, there is also a reduction in IKI size for syllable length 5, though less prominent than in the former case.

For within-word syllables the relation between IKI of the first character and onset complexity does not change with typing condition (delayed-undelayed, $F < 1$) and is essentially the same as in experiment 3. IKIs increase from one to two character onsets and they decrease for three character onsets (see Fig. 11; again, all three-character onsets (a3) consist of tri-graphs ‘sch’) and the effect was not found to be influenced by syllable length.

Fig. 11.

The differences between a1 and a2 and between a2 and a3 are significant ($p < 0.01$ and $p = 0.014$ respectively). However, onset complexity has no significant effect ($F < 1$) on ILs in delayed typing.

6.3. Discussion

The present experiment, in which we introduced an additional delay (preparation time) between stimulus presentation and commencement of typing revealed certain changes in the time structure of the typing sequence, but main characteristics remain unaffected: Words are still typed with augmented S- and SM-type IKIs (indicating that information about syllabic units within words is still retrieved and/or specified ‘on-line’, i.e. in the course of actual typing) and the delay had also no effect on within-syllable IKIs. Despite the additional preparation time there are no indications of a ‘motor input’ buffer receiving fully specified words and consequently eliminating all influences of pre-motor processing on the time structure in typing.

There were, however, two effects of ‘preparation time’. First, the significant differences between oral and visual word presentation at SM-type boundaries (see experiment 2) disappeared. Obviously, these modal differences disappear because processes involved can be, and have been, completed during the delay period. In the case of oral word presentation it seems that the selection and activation of the graphemic word form on the basis of the activated phonological word form has been completed during the preparation time.

Second, preparation time had an effect on initial latencies, i.e. the timing for the first character of a word. Two different kinds of effects on the ILs have been identified. One, the influence of number of syllables, concerns aspects of the whole word; the other, influences of syllable length and onset complexity, concerns aspects of only the first syllable. Like the disappearance of modal differences at SM-type IKIs, it is conceivable that factors reflecting features of the entire word are no longer detectable in the time structure in the case of delayed typing. However, the additional preparation time does not seem to lead to full specification at segmental (character) level as there is no significant difference in the timing of within-syllable characters between delayed and non-delayed typing.

Apparently our results concerning factors influencing the first-syllable-aspect of ILs in delayed typing are at variance with other studies. In delayed response experiments both, Sternberg et al. (1978) and Santiago et al. (2000), found that initial latencies were longer for two syllable words than for one syllable words. Further, in the same study, Santiago et al. (2000) demonstrated an effect of onset complexity for the first syllable. However, both studies dealt with oral responses. As our analyses for within-word syllables are in agreement with results of these two studies, it seems that the 'buffering' of the word initial syllable in the delayed response paradigm is mode specific, i.e. it is found in writing but not in speaking.

It is unlikely that the motor system itself is responsible for the observed effect. Ostry (1983) and Will et al. (2001) have shown that the interkey interval function has a maximum at about the fourth character position. The authors have taken this as an indication of the fact that the motor system can only initiate sequences of a maximum length of about 4 elements (i.e. characters to be typed). However, as this capacity is manifest in typing under all experimental conditions, it cannot explain the observed results (disappearance of onset-complexity and syllable length effects for the first syllable) in the case of delayed typing. It seems that under this latter condition a pre-motor buffer is recruited that receives and stores the specified first syllable from the post-lexical syllabification processes and passes it on for execution by the motor system following the 'go'-signal. Interestingly, no effects of this buffer were identified in our non-delayed experiments and it seems possible that it is not involved in normal, continuous typewriting. Furthermore, as mentioned above, existing studies indicate that such a buffer is not involved in speaking.

7. Sub-syllabic structures

We like to supply two additional results obtained from an analysis of our present corpus of typing data in German, comprising about 900 words, 1258 syllables and ca. 6200 character strokes, each word written by, on the average, 24 participants.

At the level of syllables we found a break up into obviously non-linguistic subunits. Fig. 12 is a plot of IKI means vs. their position in syllables from the German corpus. The first section of this graph, up to character position 5, corresponds well with the interkey time pattern of Larochelle (1983) and Ostry (1983). However, as we had already conjectured previously (Will et al., 2001), for long syllables there is indeed a second peak at character position 7. If the increase of IKIs is taken as a reflection of the time demands for preparation of the subsequent sequence (Ostry, 1983) the graph suggests that syllables are probably processed in sub-units of three characters. However, there seems to be some flexibility in the placement of the break up as we have obtained first within-syllable maxima at 3rd, 4th and 5th character position, indicating that the actual length of the processed sub-units are not independent of the context, i.e. the actual syllable composition. The question whether this intra-syllable function is a reflection of autonomous motor processing or to what degree it is conditioned by the structure of the units that are processed (syllables), obviously needs further research.

Fig. 12.

Another type of sub-syllabic unit is indicated by the IKI pattern of geminated letters. It has already been mentioned that in character repetitions the IKIs leading to the repeated character are always shorter than the previous one (see Fig. 13).

Fig. 13.

An explanation could be that for geminate pairs the motor program only has to execute instructions for one specified character plus a ‘repeat’ instruction, and that is obviously faster than the execution of instructions for two specified characters. Our chronometrical data support the idea of the special status and the unity of geminated character pairs that has been developed on the basis of clinical studies (Caramazza & Miceli, 1990; McCloskey et al., 1994; Miceli et al., 1995). Interestingly, if we compare gemination at within-syllable positions, across S-type and across SM-type boundaries (Fig. 13), there are essential differences between the latter two. If gemination occurs across S-type boundaries IKIs for the repeated character do not differ significantly from those of within-syllable geminates. In contrast, the second character of a gemination across SM-type boundaries is significantly longer (> 100 ms) than those of either the S- or L-type. In other words, gemination seems to have an effect on the processing of S-type segmentation, but not, or not noticeable on SM-type segmentation.

8. General Discussion

A wealth of studies using a variety of approaches have investigated typing as skilled motor behavior (for an overview, see Cooper 1983). They have revealed a set of factors constraining the timing of keystrokes that range from keyboard layout, aspects of motor programming and motor performance, to the influence of character sequences, i.e. keystroke context (review e.g., Norman & Rumelhart, 1983). However, all experiments of the present study demonstrate that, after taking those ‘motor’ factors into account, there is also a significant influence of linguistic factors on keystroke timing: the sequence of interkey intervals in discontinuous word typing is noticeably structured by the occurrence of increased interkey intervals at syllable and combined syllable/morpheme boundaries (Fig. 14). Henry and Rogers (1960) were probably the first to propose that changes in reaction time (latency) might reflect changes in movement sequence preparation and they proposed a model in which part of the reaction time is needed to gain access to stored information concerning the whole sequence. In accordance with other research on typewriting, we therefore consider at least parts of the augmented interkey time to represent time needed for preparing subsequent sequences.

Fig. 14.

Different hierarchical ‘layers’ are reflected in the time structure of IKI sequences:

1) Individual keystrokes. These have been shown to depend on a set of various factors like typing speed, keyboard layout, constraints of hand and finger movement, character context, character frequency of occurrence in a language (Gentner, 1983; Larochelle, 1983; Ostry, 1980, 1983, Shaffer, 1978; Sternberg et al., 1978; Will et al., 2001)

2) Sub-syllabic segmentation: in syllables with more than 4 characters there is an augmented IKI at the fourth character position, about 10 - 30 ms larger than the average within-syllable IKI. It is thought to indicate a break up of syllables into distinct motor sequences (Ostry, 1983). We suggest that this segmentation corresponds to the serial position effect described by Larochelle (1983) and Ostry (1983), except that we have identified it on syllable and not on word level.

3) Syllabic segmentation: Syllable boundaries that were not at the same time morpheme boundaries show increased IKIs, 20 - 80 ms larger

than the average within-syllable IKIs. S-type IKIs were not found to be influenced by word frequency with visual or aural word presentation and S-type segmentation seems to be lexicon independent in these cases (Nottbusch and Weingarten, 2000). However, this type of segmentation is also present in picture naming when all information necessary for typing has to be derived from the lexicon. It is likewise present in typing of pseudo-words. Therefore, S-type segmentation probably can be produced by lexically as well as extra-lexically processed word encoding and is most likely generated at post-lexical levels. S-type segmentations can be suppressed or overridden by certain factors, two of which were word frequency and gemination. That these syllabic effects do not necessarily imply phonological processes can be explicated through the concept of an autonomous orthographic syllable (Olson & Nickerson, 2001).

4) Syllabic-morphemic segmentation (SM-type segmentation): Combined syllable and morpheme boundaries are marked by IKIs, 80-300 ms larger than the average within-syllable character IKI. This segmentation was found to be influenced by word frequency and hence can be considered lexicon dependent. It probably reflects basic information about syllable and morpheme structures as stored in the lexicon. SM-type IKIs contain information about two different linguistic levels. Besides information about the SM-unit concerned (e.g. the number of syllables) it also contains S-type information about the first syllable in the unit because SM-units comprise at least one complete syllable.

The finding that pure M-type IKIs (IKIs at pure morpheme boundaries) are not distinguishable from L-type IKIs in terms of timing seems somewhat surprising in the light of theories of language production like that of Levelt (1989) in which information about morphological structure is a central aspect of information activated in and retrieved from the wordform lexicon. There is even evidence that is taken to suggest that morphemes within words may be segmented and recognized independently in reading (Morton, 1979). As already mentioned above, in the case of typing following written or oral word presentation it can be argued that our results are due to the fact that the experiments did not require active wordform construction (wordforms are predetermined by the word stimuli). This cannot be maintained, however, for our picture naming experiment, yielding the same results for the M-type IKIs as the other experiments. It seems that our results are much more compatible with models like that proposed by Butterworth, who assumes that word forms are not generally derived on-line from morphemic components. Instead, he proposes that information about morphology and lexical rules are deployed only when word search fails to retrieve a phonological lexical representation (Butterworth, 1992). It is conceivable that the reported differences between SM- and M-units do in fact reflect differences in lexical representation of different types of morphemes (as M-units are not root-morphemes).

Concerning the locus of origin of S- and SM-type segmentation in relation to existing models of language processing the following points might be considered: The existence of S- and SM-type segmentations in both, handwriting (Nottbusch et al., 1998), as well as typewriting, suggests that the origin of both is prior to the allographic conversion module. S-type segmentation might arise at a level corresponding to the graphemic output buffer. According to the logogen model, information about words as well as pseudo-words can be processed at this level (see Caramazza et al., 1987). Caramazza & Miceli (1990) proposed that the graphemic representation at this level consists of multidimensional structures, consisting of independent information about graphemic features of a word like grapheme identity, number of graphemes, gemination, C/V status of graphemes and syllabic units or syllable boundaries. In the present study we have demonstrated that most of these features are reflected in the timing of S-type IKIs and Will et al. (2001) have also demonstrated a conservation of the C/V status in typing errors. However, the word frequency effect on SM-type segmentation obviously is not compatible with the graphemic output-buffer concept as proposed by Caramazza and Miceli (1990) and this type of segmentation is most likely due to lexical influences or effects thereof. This suggests, that the motor system might receive information from at least two different levels of the word processing hierarchy simultaneously, and the pathways by which this information is transmitted probably connect with those of the dual route model of reading as for example proposed by Zorzi et al. (1998).

In the domain of continuous activities like language production, the programming or organization of the activities has been considered essentially hierarchical because the unit of activity that is ‘programmed’ is larger than the unit of response (Lashley, 1951). Such a concept forms the basis for models of written language production like that for handwriting by Van Galen (1991), and it comes as no surprise that our present study on typing indicates a hierarchy of ‘planning units’ on the basis of duration of planning time and functional dependencies. What is remarkable, though, is that there seem to be direct influences of central linguistic processing stages on the timing in normal as well as delayed typing. These findings pose serious problems for theories that assume a strict serial arrangement for linguistic and motor processing in written word production. At least an extension of these assumptions to typewriting is not supported by our data. For example, the Van Galen (1991) model assumes that each of the hierarchical processing modules is equipped with a buffer to avoid timing conflicts between the modules. Concurrent activities of higher units are thought to increase the processing load, thereby affecting (reducing) production speed in a time-shifted manner, the additional load occurring in advance of the respective linguistic unit. However, due to the interposed buffers, functional dependencies on higher hierarchical units should not be detectable at lower levels. In contrast, the present study demonstrates influences of higher hierarchical units on the timing of the output and their persistence in the case of delayed typing, suggesting that motor processes and higher linguistic word processing levels are not 'decoupled' by interposed temporary buffers. This interpretation hinges on the locus of the word frequency effect, which has been demonstrated to be at lexical (Jescheniak and Levelt , 1994; Caramazza et al., 2001), not at sub- or post lexical level. The model that emerges from our results nevertheless seems be compatible with and may even require short term memory mechanisms like feed back loops at lexical level to maintain or update activation, but it appears to be incompatible with post lexical memory buffers. Timing conflicts in this model are avoided because words are processed in sequences of sub-word units and the different processing levels (lexical, post-lexical, motor) work in parallel. It seems, the motor system does not work like a module in the sense that its is informationally and operationally encapsulated from other structures and processes (e.g., Fodor, 1983). On the contrary, it seems to operate in tight connection and cooperation with various hierarchical levels of the language processing system. It resembles an interactive associative network structure in the sense of Posner and Carr (1992) more than a self-sufficient modular component. It is precisely this aspect which makes typing experiments an interesting tool in the further exploration of language production processes.

APPENDIX A

Fig. A1.
Fig. A2.

APPENDIX B (Wordlists)

Experiment 1 (English words, visual presentation)			
ab*stain	af*fec*t#ing	am*bi*t#ion	as*tro*no*m#er
awe+some	birth+right	care+ful	con*foun*d#ed
con*script	con*tai*n#er	de*tract	de*pen*d#ence
dis*dain	dis+gus*t#ed	dis+trait	en*coun*t#er
en*croach	for*mu*la	han*d#y+man	hand+shake
haugh*ty	im*mer*s#ion	im*mu*n#i*ty	im+mor*t#al
in*ci*den*t#al	in+for*m#al	le*gen*d#a*ry	left+han*d#er
light+ly	mo*du*la*t#ed	moun*tain	moun*t#ed
nor*th#ern	ob*ser*v#ant	out+house	out+skirts
per+cep*t#ive	pro+spect	quan*t#i*fy	re+mar*k#a*ble
round+house	round+up	scrip*t#ing	side+win*d#er
some+one	thought+ful	trai*t#or	un+ex*pec*t#ed

+ indicates syllable + morpheme boundaries, SM (n = 22)
* indicates syllable boundaries, S (n = 57)
# indicates morpheme boundaries, M (n = 27)

Experiment 2 (German words, oral presentation)			
ab+ge+lau*f#en	auf+sa*g#en	aus+he*b#en	Bar
Be*ton+klotz	Bie*ne#n	Bir*ne#n	blau+grau
Boot	Bus	ein+la*d#en	ent+he*b#en
ent+la*d#en	Farb+fo*to	Farb+pho*to	Fix+stern
Gar*ten+haus	ge+lau*f#en	Gleit+schuh	glimpf+lich
grau+blau	Hand+schrift	Haus+gar*ten	Haus+tür
hin+durch	Holz+scheit	Jahr	kam
Kan*ne	Kan*te	Kluft	Knust
Kraft+akt	Kraft+protz	Küs*te	Le*b#en
leh*n#en	Lie*b#e	Lin*de	Lust
Not	Ohr	Ort	ran
sa*g#en	Sand+strand	Schin*ken	Schreib+hand
sin*k#en	Steck+do*se#n	stein+alt	Streit+fall
Strom+ka*bel	Tür+schild	um+fah*r#en	um+fah*r#en
um+ler*n#en	um+rin*g#en	un*ter+le*g#en	un*ter+le*g#en
un*ter+mau*er#n	un*ter+sin*k#en	Un*ter+stand	un+ver+sehr#t
ver+le*s#en	ver+sa*g#en	ver+sehr#t	vor+le*s#en
weg+le*g#en	Wind+hund	Wüs*t#e	Wust
Wut	zah*l#en	Zahn	Zaun
zer+le*g#en			

49 SM , 46 S, 32 M

Experiment 3 (Comparison of typing picture names and visually presented words (German))

A*mei*se	A*na*nas	A*sche#n+be*cher	Ba*na*ne
Bü*gel+brett	Bü*gel+ei*sen	Eich+hörn+chen	Erd+bee*re
Fahr+rad	Ga*bel	Hub+schrau*b#er	Ka*no*ne
Kin*d#er+wa*gen	Kro*ko*dil	Kro*ne	Last+wa*gen
Luft+bal*lon	Mais+kol*ben	Mo*tor+rad	Nas+horn
Plat*te#n+spie*l#er	Roll+schuh	Schau*kel	Schau*kel+stuhl
Schild+krö*te	Schmet*ter+ling	Schnee+mann	Schreib+tisch
Spinn+rad	Te*le*fon	Tril*ler+pfei*fe	Trom*pe*te
Wä*sche+klam*mer	Wind+müh*le	Zahn+bürs*te	Ze*bra
26 SM, 42 S, 5 M			

Experiment 4 (Typing of visually presented pronounceable (German) pseudo-words)

pseudowords with unambiguous syllable structure (final syllables of the words ‚Sokalier‘ and ‚Nitretostar‘ were not considered because they are not unambiguous)

Au*re*lu	Ba*to*nik	Be*ot*mang	Bram*pa*te
Fa*nu*mest	Fapp*sche	gils*barn	La*na*be
Mie*be	Mie*la	Ni*tre*tostar	Raf*ta*lon
Ra*te*nok	Schma*be*ot	So*ka*lier	U*bei*se

pseudowords with ambisyllabic syllable structure

Bri*scher	Bram*mer	Graf*friel	Lam*me
Schmal*ler*bing	Stel*lurt		

Experiment 5 (Comparison of delayed-typing of orally and visually presented words with undelayed typing)			
1 syllable, 4 letters			
Berg	Hemd	Kind	
1 syllable, 5 letters			
Brett	Stein	Tisch	
1 syllable, 6 letters			
Dienst	Freund	Strand	
2 syllables, 4 (1+3) letters			
A*tom	E*sel	U*fer	
2 syllables, 4 (2+2) letters			
Au*ge	Da*me	Er*de	
2 syllables, 5 (2+3) letters			
Fe*der	Ha*fen	Ka*bel	
2 syllables, 5 (3+2) letters			
Blu*me	Kis*te	Kli*ma	
2 syllables, 6 (2+4) letters			
Be+darf	Er+folg	Ge+fahr	
2 syllables, 6 (3+3) letters			
Alt+bau	Bal*ken	Erb+gut	Ent+zug
Erd+gas	Fel*sen	Han*del	Irr+tum
Rad+ler	Ver+bot	Ver+zug	Wag+nis
2 syllables, 7 (2+5) letters			
Be+richt	Be+stand	Ge+dicht	
2 syllables, 7 (3+4) letters			
Bau+plan	Ein+heit	Ent+wurf	Erb+teil
Hab+gier	Kir*sche	Neu+heit	Neu+ling
Par*kett	Stu*dent	Ver+band	Zer+fall
2 syllables, 7 (4+3) letters			
Drei+eck	Gast+hof	Holz+weg	Klau*sur
Prin*zip	Rinn+sal	Skan*dal	Wild+nis
Zeug*nis			
2 syllables, 8 (2+6) letters			
Be+scheid	Ge+brauch	Ge+spenst	
2 syllables, 8 (4+4) letters			
Berg+mann	Kauf+haus	Land+luft	
2 syllables, 8 (5+3) letters			
Fried+hof	Spinn+rad	Stand+ort	
2 syllables, 9 (4+5) letters			
Blau+licht	Flug+blatt	Kauf+kraft	
2 syllables, 9 (6+3) letters			
Dienst+weg	Schiff+bau	Strand+bad	

2 syllables, 10 (4+6) letters		
Herz+schlag	Laub+frosch	Such+dienst
3 syllables, 6 (2+2+2) letters		
An*ti*ke	Ba*na*ne	Eu*ro*pa
3 syllables, 7 (2+2+3) letters		
Al*ko*hol	Bo*ta*nik	Ka*me*rad
3 syllables, 7 (3+2+2) letters		
For*tu*na	Pra*li*ne	Tor*na*do
3 syllables, 8 (2+2+4) letters		
De*mo*krat	Do*ku*ment	Ma*ni*fest
3 syllables, 8 (3+2+3) letters		
Alt+ei*sen	Erd+be*ben	Rat+ge*ber
3 syllables, 8 (4+2+2) letters		
Schi*ka*ne	Stra*te*ge	Trom*pe*te
3 syllables, 12 (4+4+4) letters		
Fach+werk+haus	Voll+korn+brot	Wild+west+film
4 syllables, 7 (1+2+2+2) letters		
A*ma*zo*ne	A*me*ri*ka	E*pi*so*de
4 syllables, 8 (2+2+2+2) letters		
An*ti*lo*pe	Li*mo*na*de	Pa*no*ra*ma
4 syllables, 16 (4+4+4+4) letters		
Baum+woll+hals+tuch	Fach+werk+haus+dach	Hand+ball+hand+buch

65 SM, 73 S

Acknowledgements

We like to thank the staff members at UNE, Armidale and Flinders University, Adelaide for participating in the experiments, E. Crosby for her invaluable help with conducting the experiments at UNE, B. Weingarten for assisting in the preparation of the audio material for the German experiments, Drs. Th. Pechman and G. Blanken for reading and commenting on earlier versions of the manuscript, and Ph. Cummins for checking the final version.

This research was supported by a Grant from the German Science Foundation (DFG, Schwerpunktprogramm “Sprachproduktion”) to R. Weingarten.

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Figures

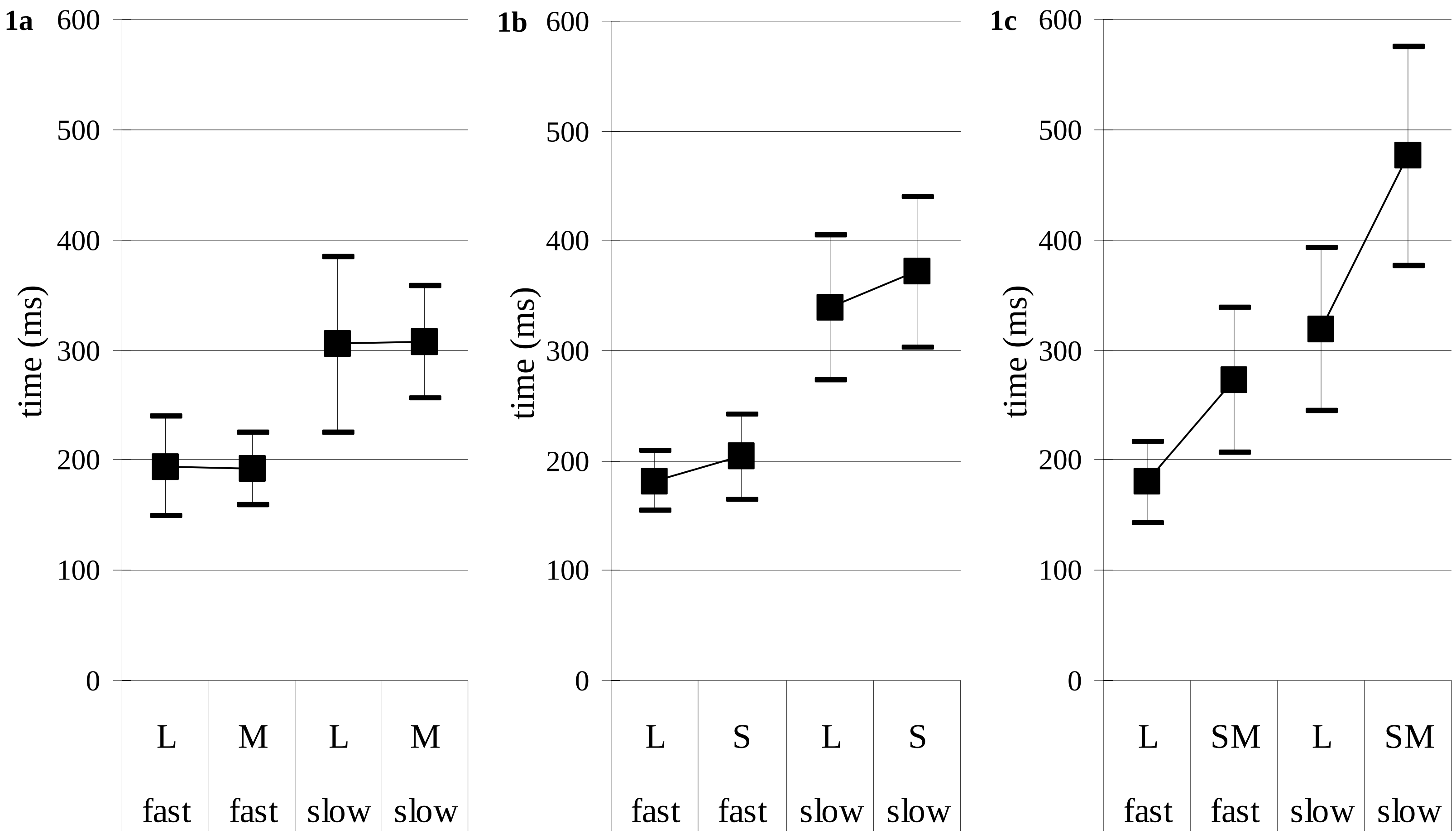

Fig. 1 a-c. *Means ± 1 standard deviation for L- vs. M-type (a), L- vs. S-type (b), L- vs. SM-type(c) IKIs, each comparison for both speed groups. (Note: The different values for the L-type IKIs are due to different digraph sets.)*

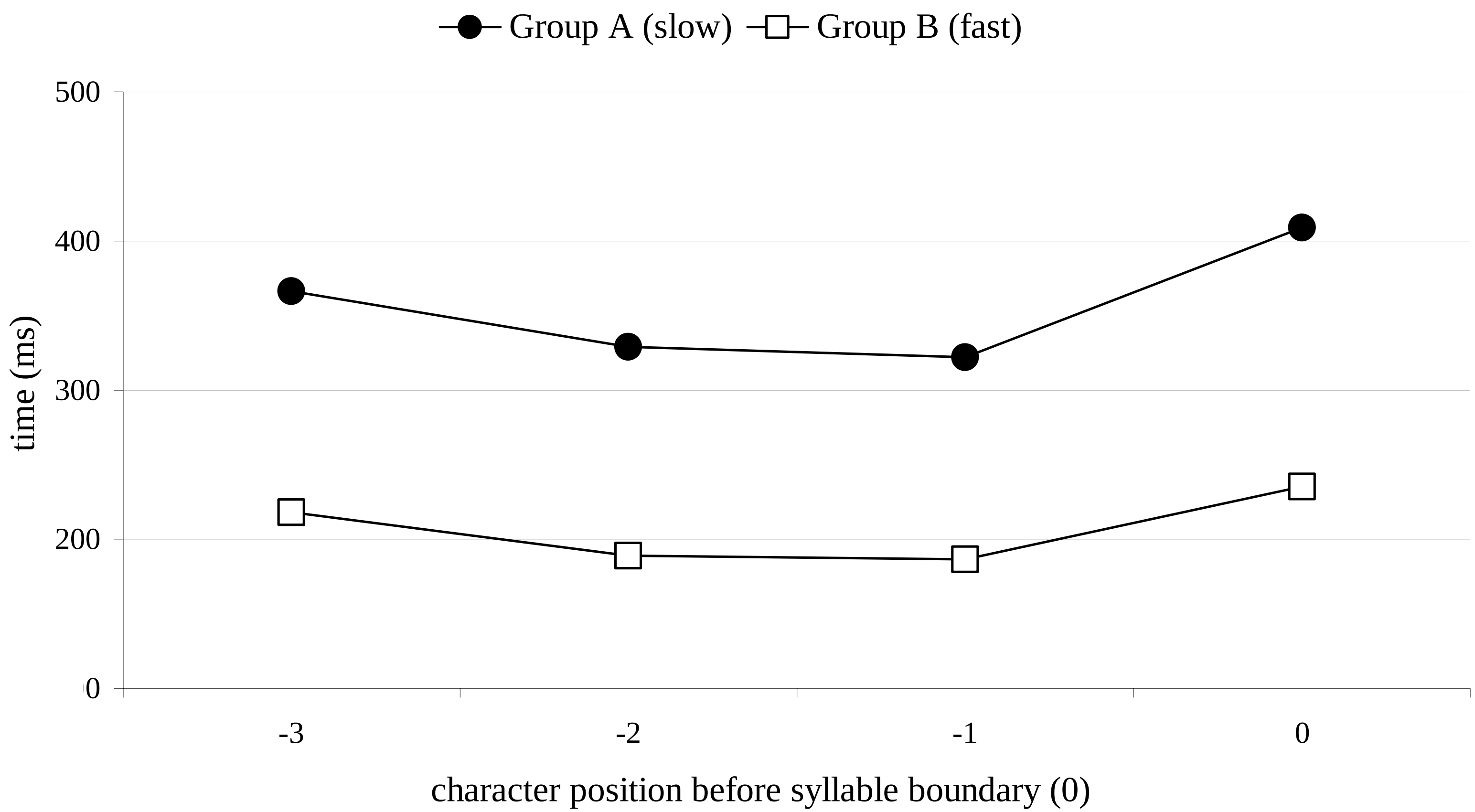

Fig. 2. *Mean IKIs in position 1 to 3 before a syllable boundary (at pos. 0)*

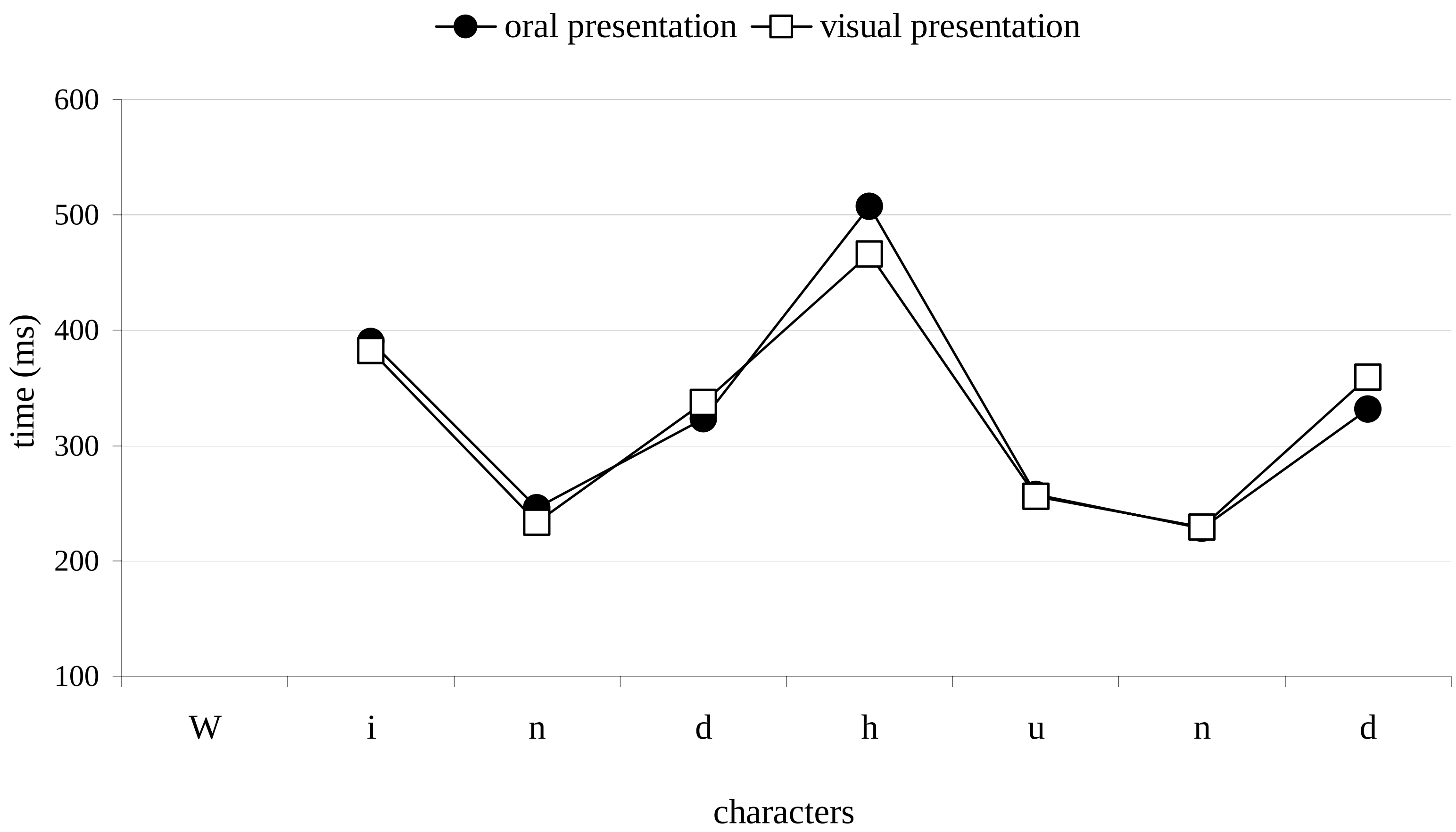

Fig. 3. *Comparison of IKI sequences under visual and oral presentation of the German word 'Windhund' (Greyhound).*

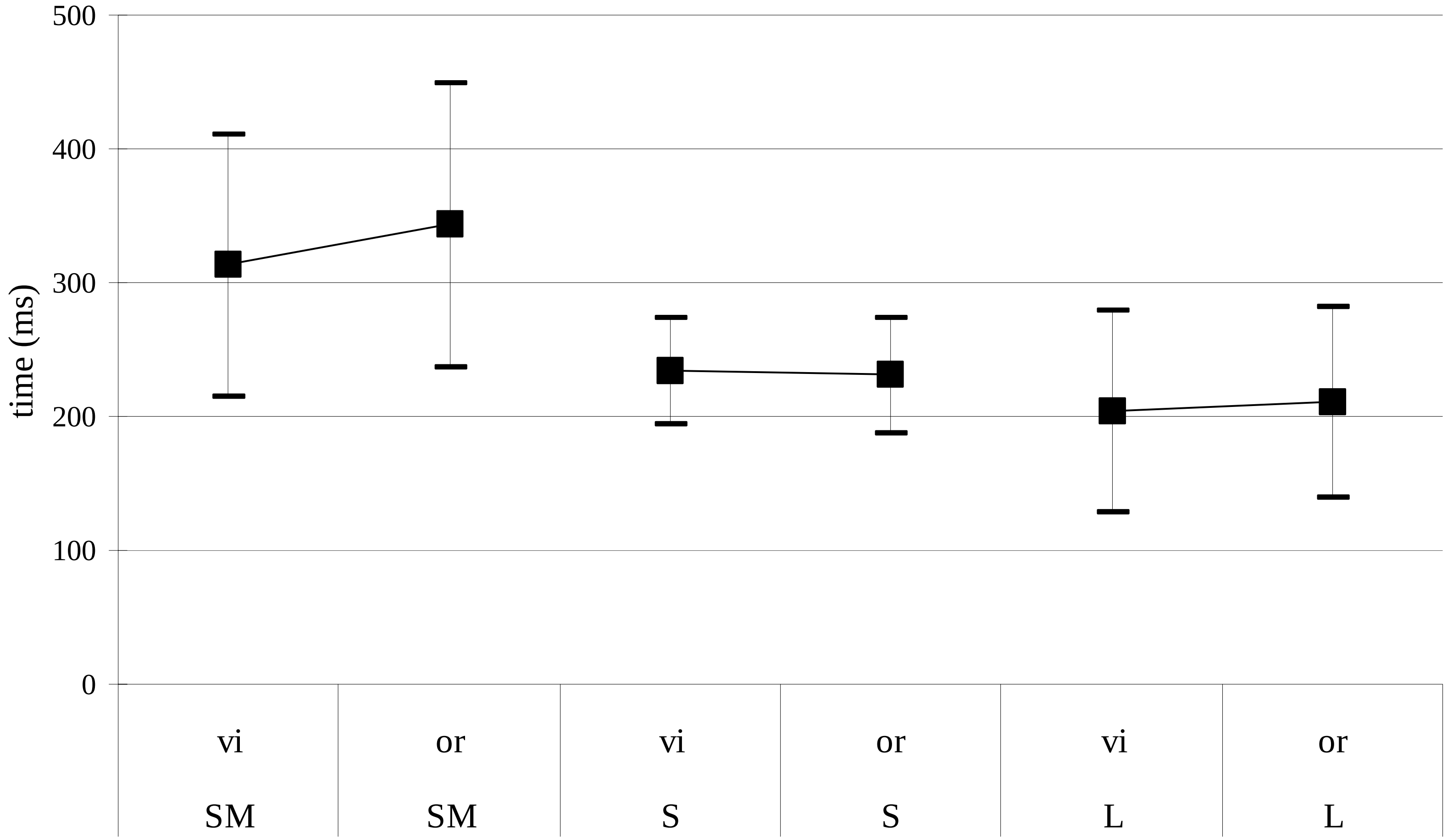

Fig. 4. *Comparison of means ± 1 standard deviation for SM-, S- and L-type IKIs after visual (vi) and oral (or) presentation (fast typists).*

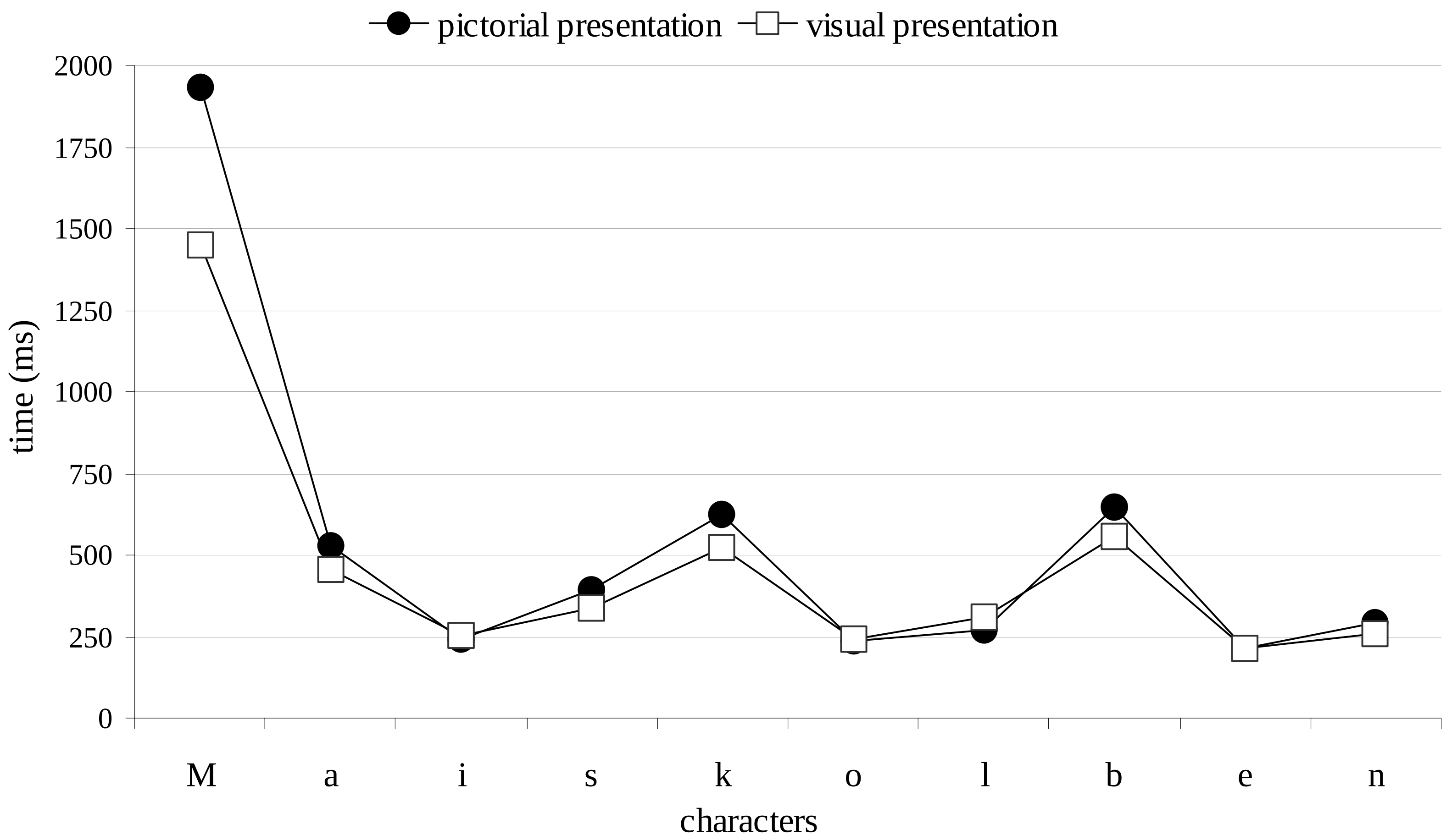

Fig. 5. *Comparison of mean ILs and IKIs for the German word 'Maiskolben' (corn-cob) in picture naming and visual word presentation condition (slow typists).*

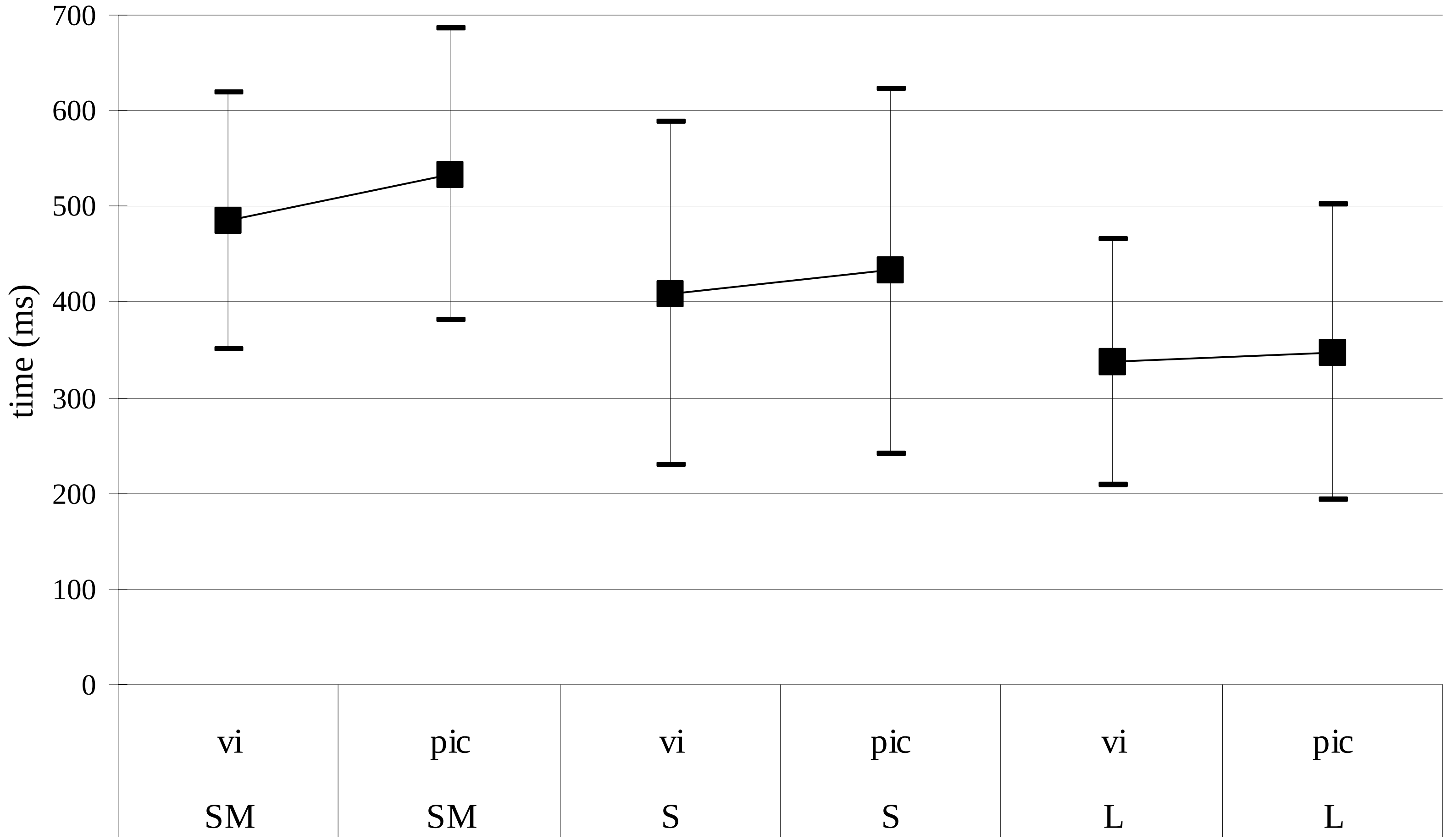

Fig. 6. *Comparison of means ± 1 standard deviation for SM-, S- and L-type IKIs after visual (vi) and pictorial (pic) presentation (slow typists).*

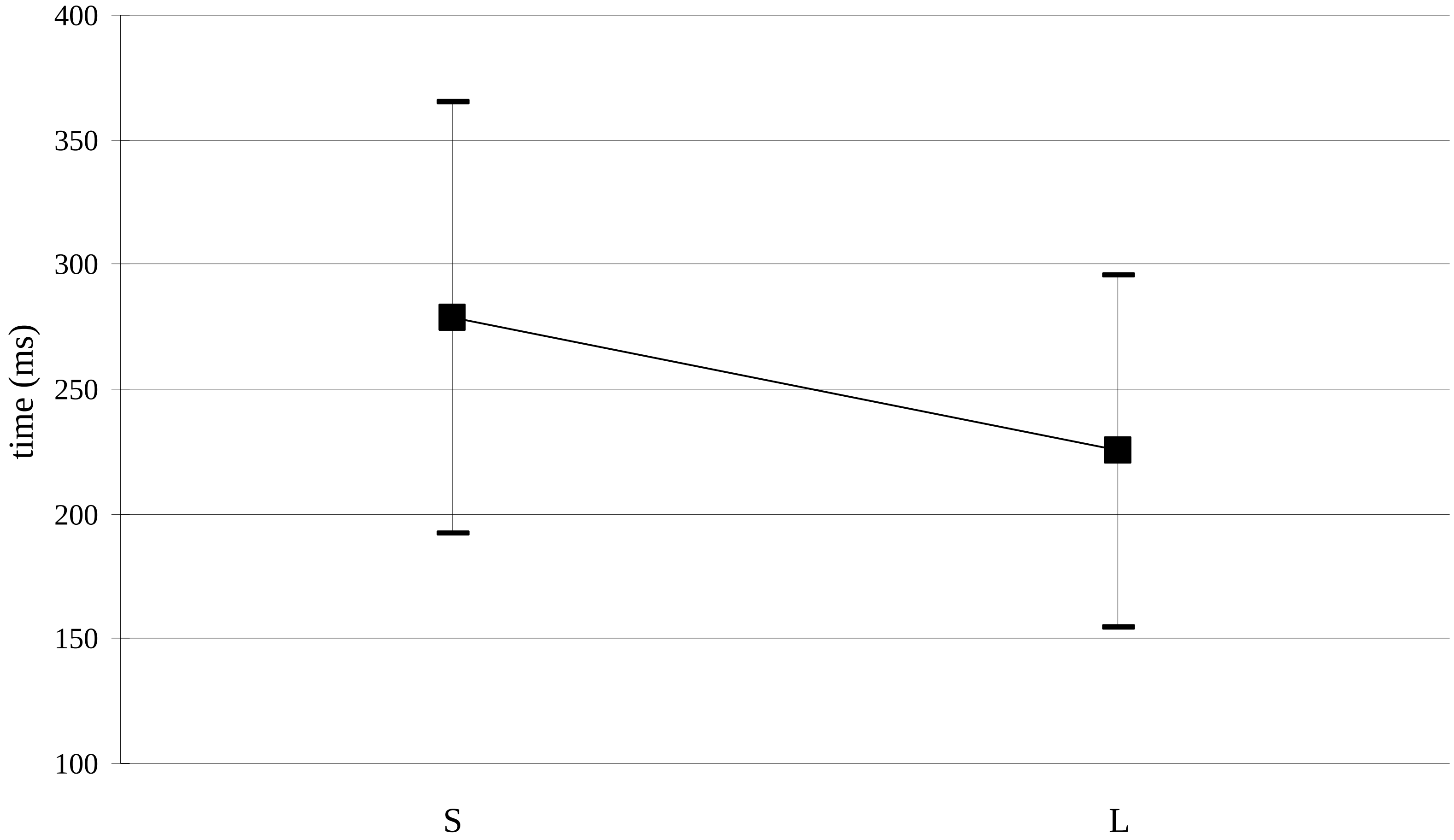

Fig. 7. *Comparison of means ± 1 standard deviation for S- and L-type IKIs in pseudowords.*

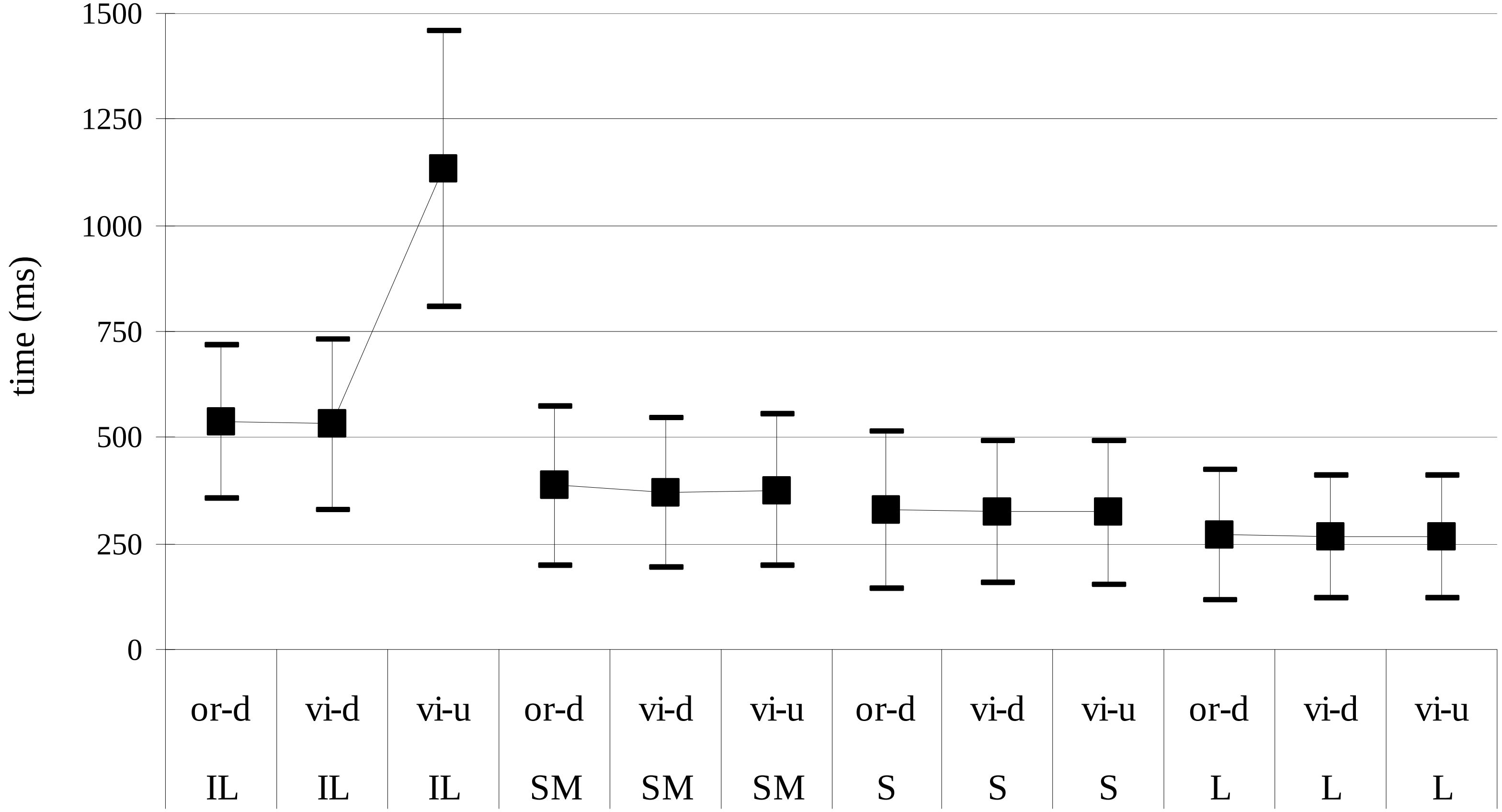

Fig. 8. *Comparison of means ± 1 standard deviation for Initial Latencies and SM-, S- and L-type IKIs after delayed oral presentation (or-d), delayed visual presentation (vi-d) and undelayed visual presentation (vi-u).*

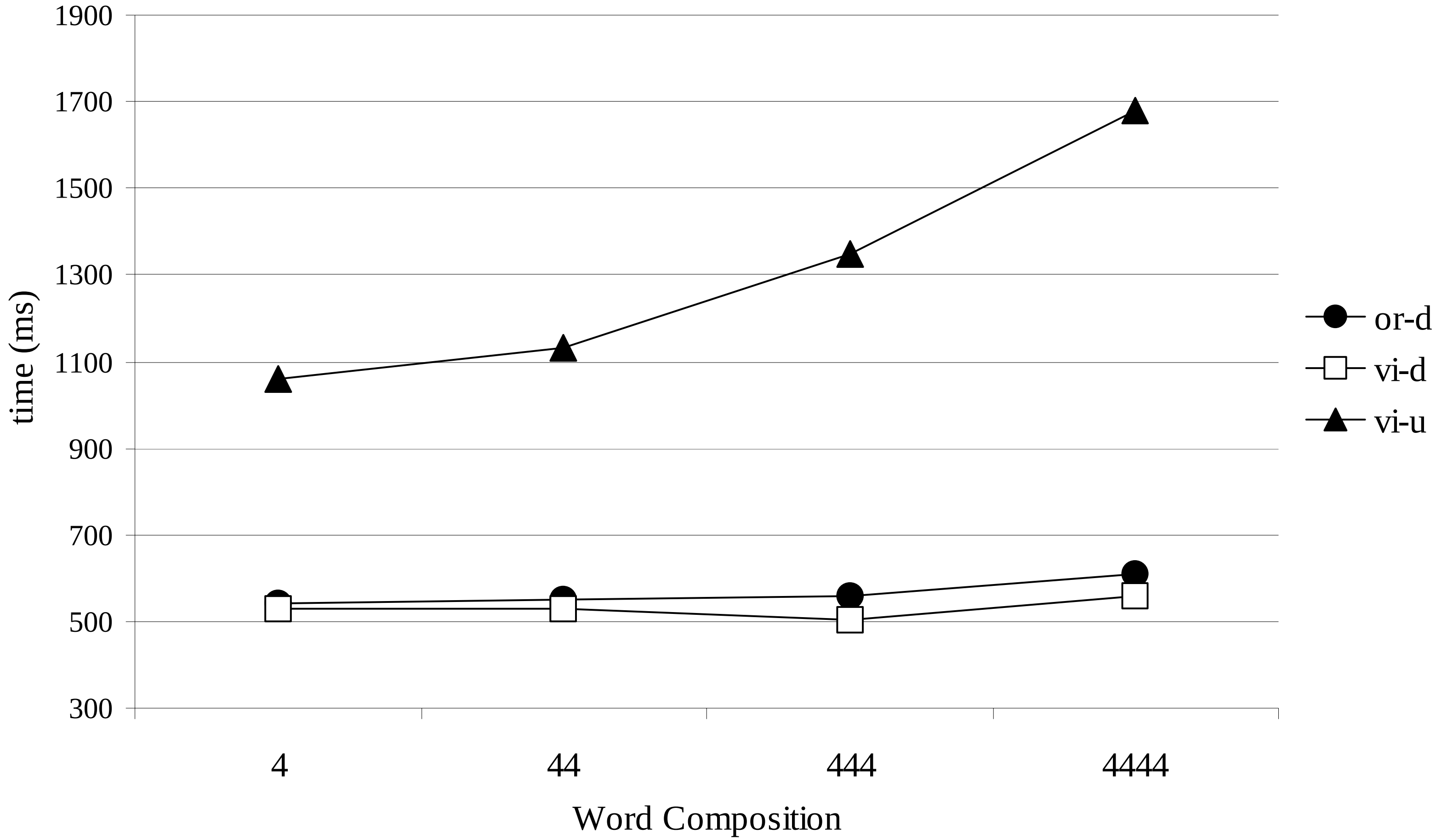

Fig. 9. *Influence of the number of syllables per word on mean ILs. Mean IKIs for 1 to 4-syllable words, each syllable containing 4 characters. or-d = delayed oral word presentation, vi-d = delayed visual word presentation, vi-u = undelayed visual word presentation.*

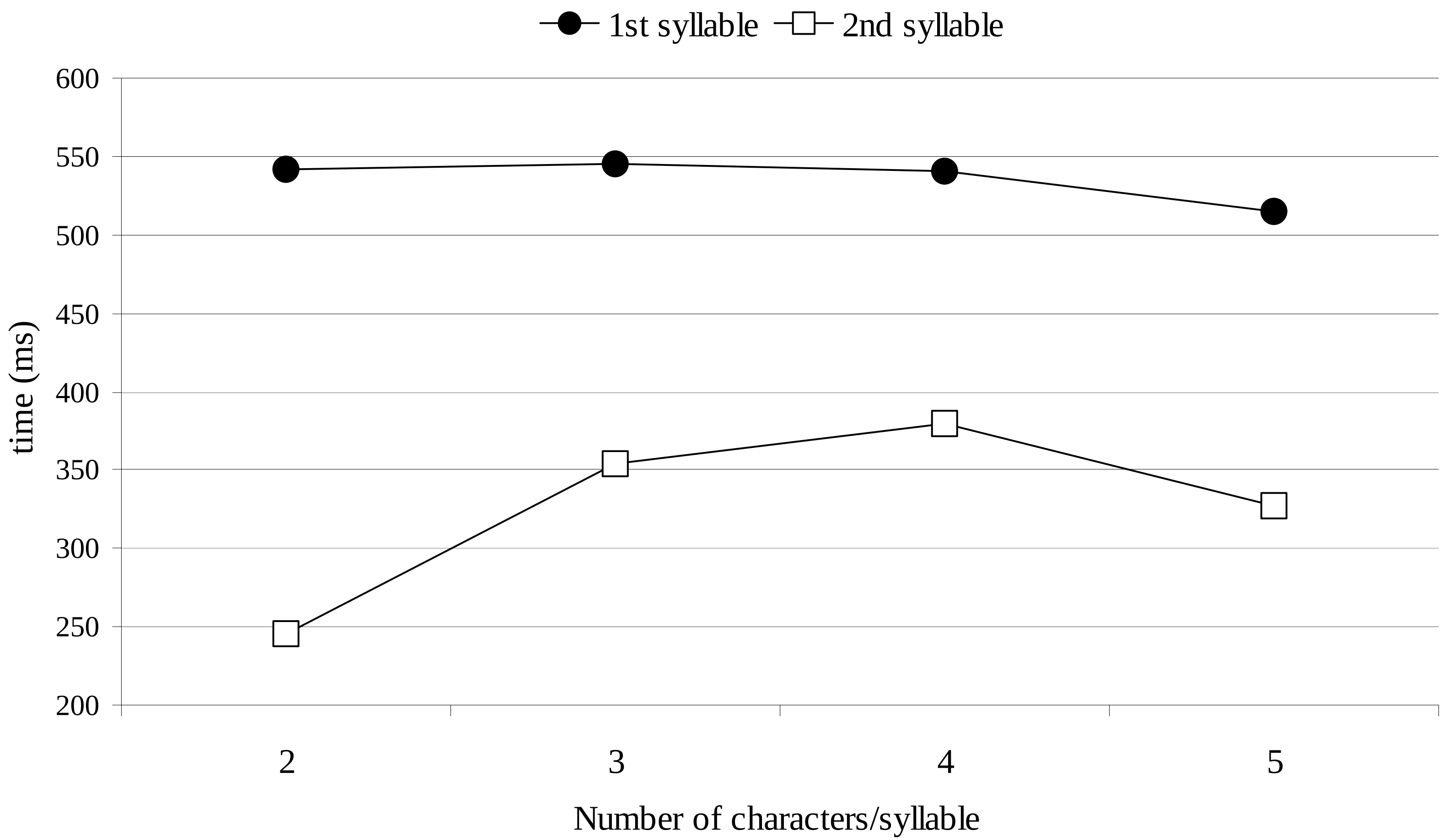

Fig. 10. *Influence of syllable length on mean IL (1st syllable) or mean IKIs (2nd syllable) for the first character of syllables in delayed typing. Words were bi-syllabic and either the first or the second syllable had constant length of 3 characters*

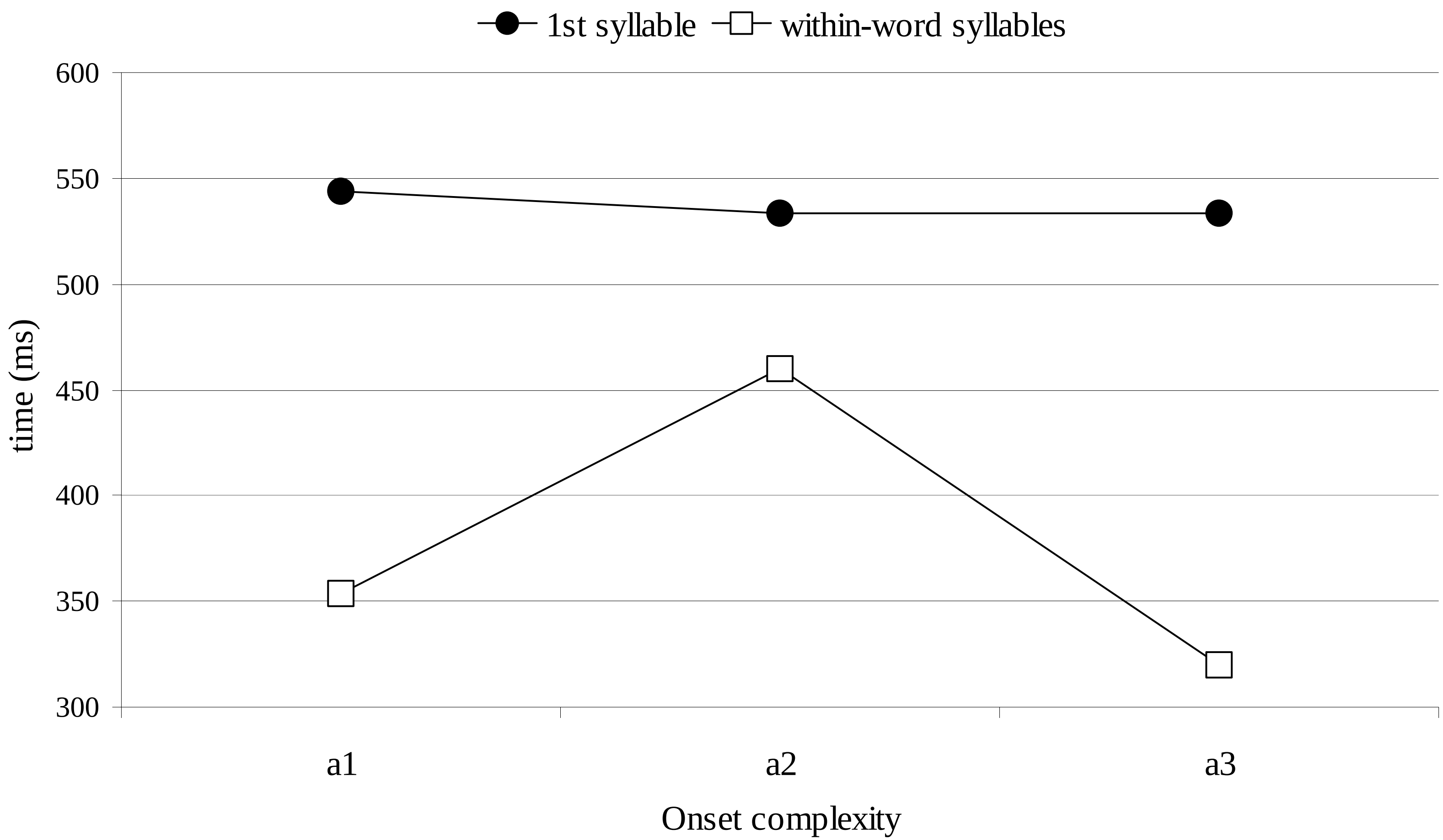

Fig. 11. *Influence of onset complexity on mean IKIs for the first character of syllables in delayed typing (1st syllable = first syllable in words).*

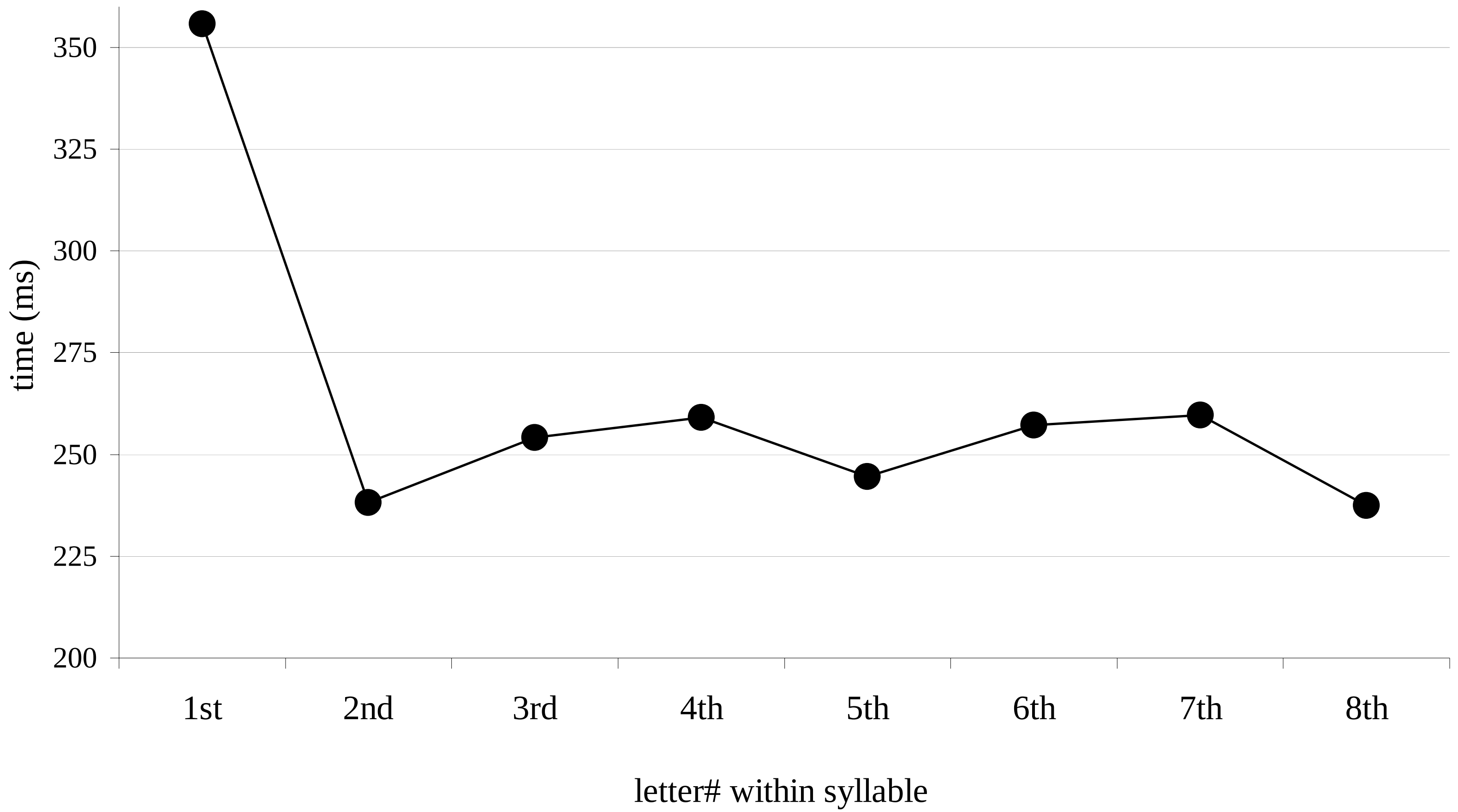

Fig. 12. *Mean IKI vs. character position within syllables. N=1258 syllables (German)*

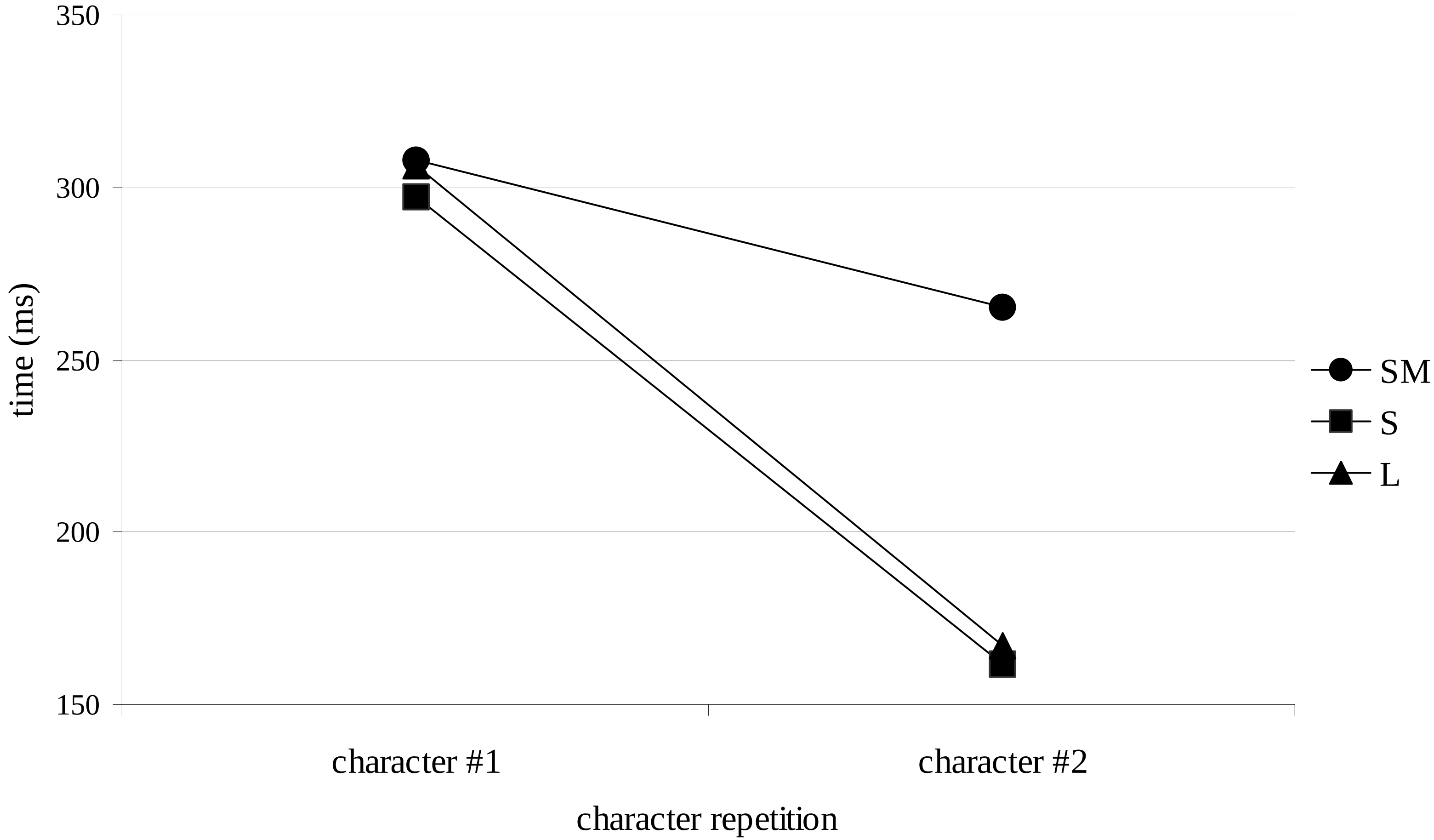

Fig. 13. *Mean IKIs for geminated characters from our corpus of typing data in German (140 geminations). L= both characters at within-syllable position; S and SM = gemination across S- or SM-type boundary, respectively.*

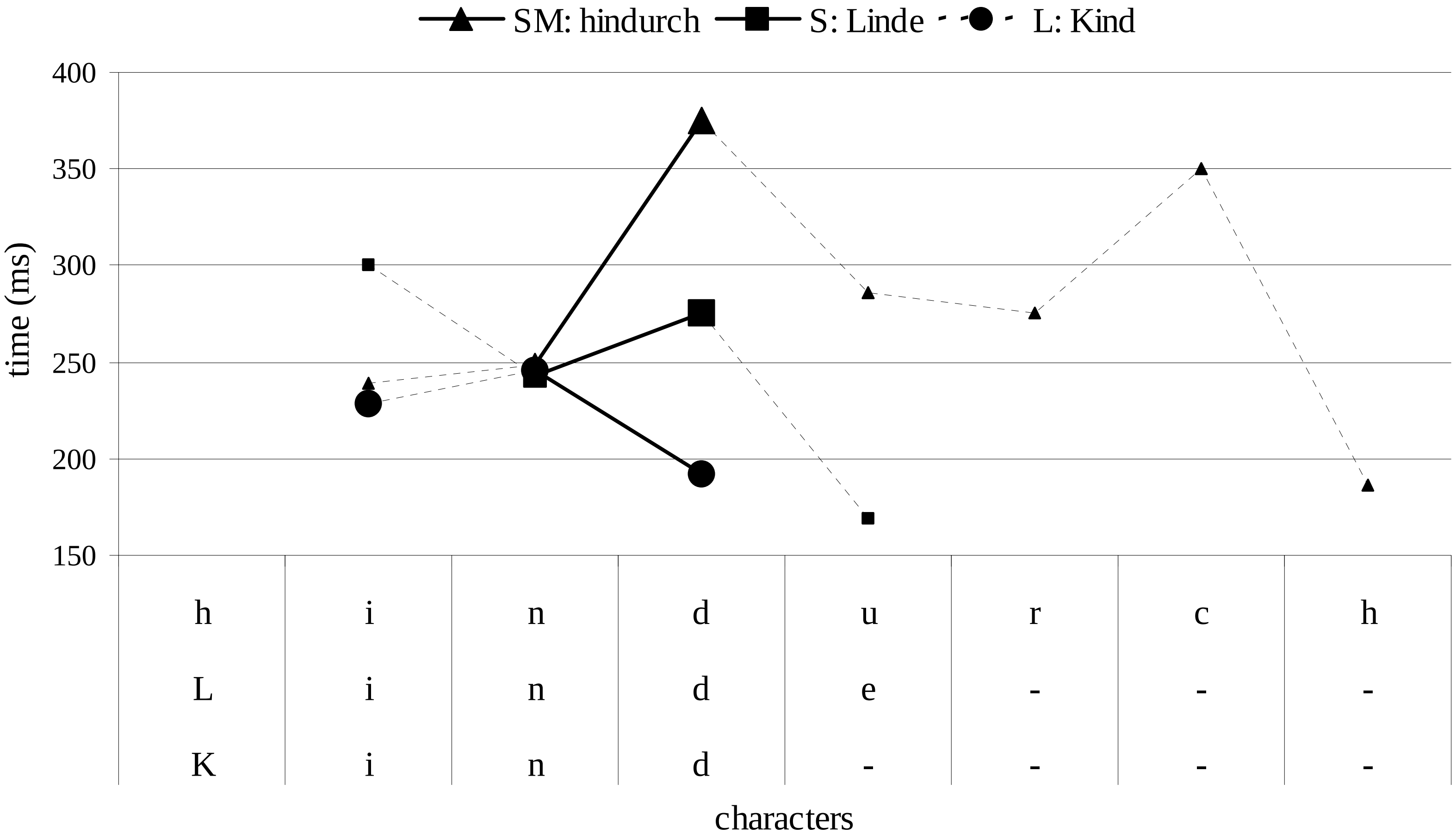

Fig. 14. *Summary of methodology and results of IKI analysis. Interkey intervals between characters of identical digraphs (<nd>) located at different linguistic boundaries (at combined syllable/morpheme (SM-type) boundary in 'hindurch' [throughout], syllable (S-type) boundary in 'Linde' [lime tree] and at within-syllable position (L-type) in 'Kind' [child]. The fact that the L-type 'd' is in final character position in this example is not decisive, L-type IKIs are generally shorter than the other types independent of their position within words). All three IKI-types for the*

character <d> have different size and for all digraphs these differences were significant. Initial latencies have been omitted in this figure.

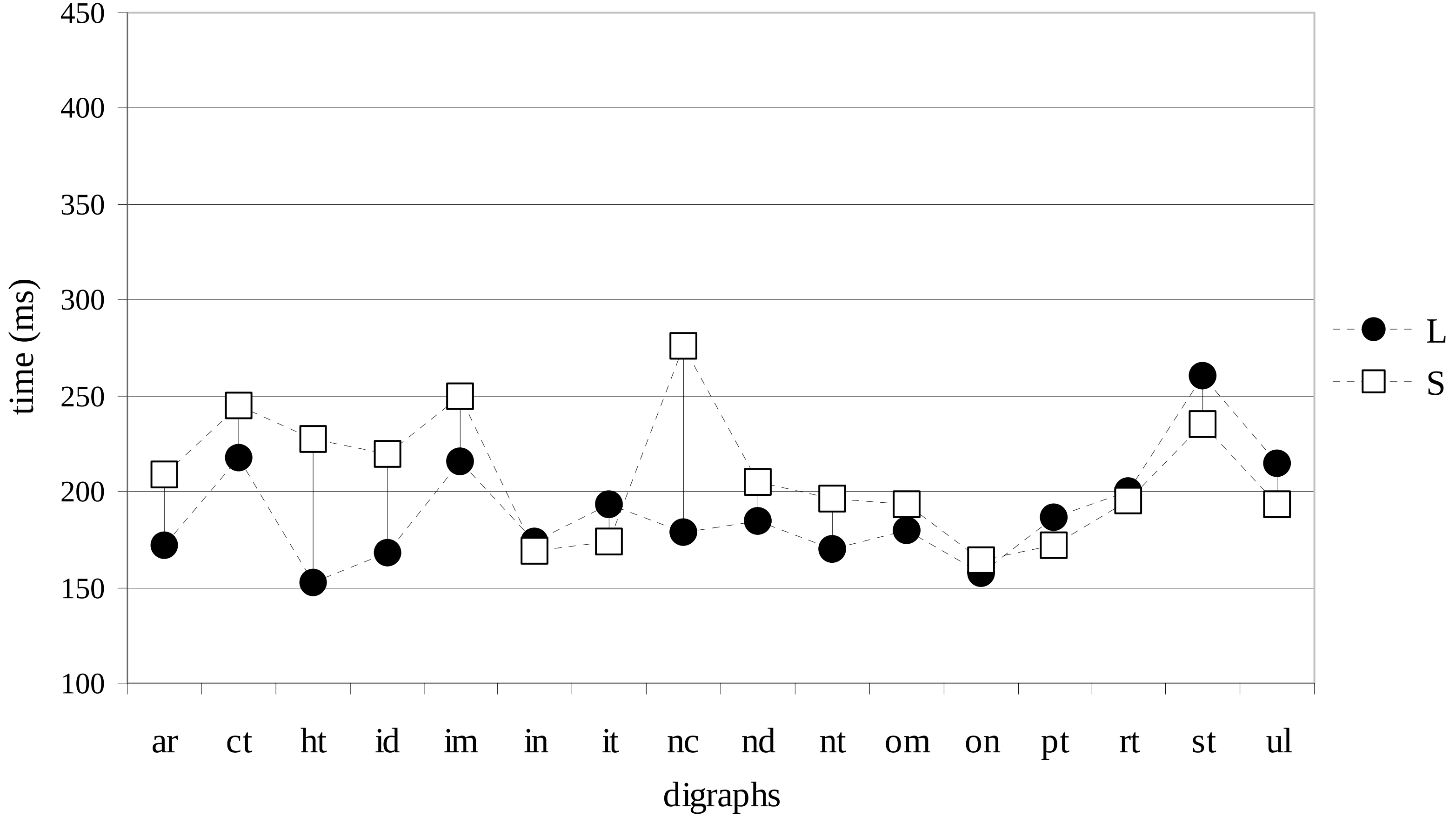

Fig. A1. *Digraph means from experiment 1 for S-type IKIs in comparison with corresponding L-type IKI (fast typists).*

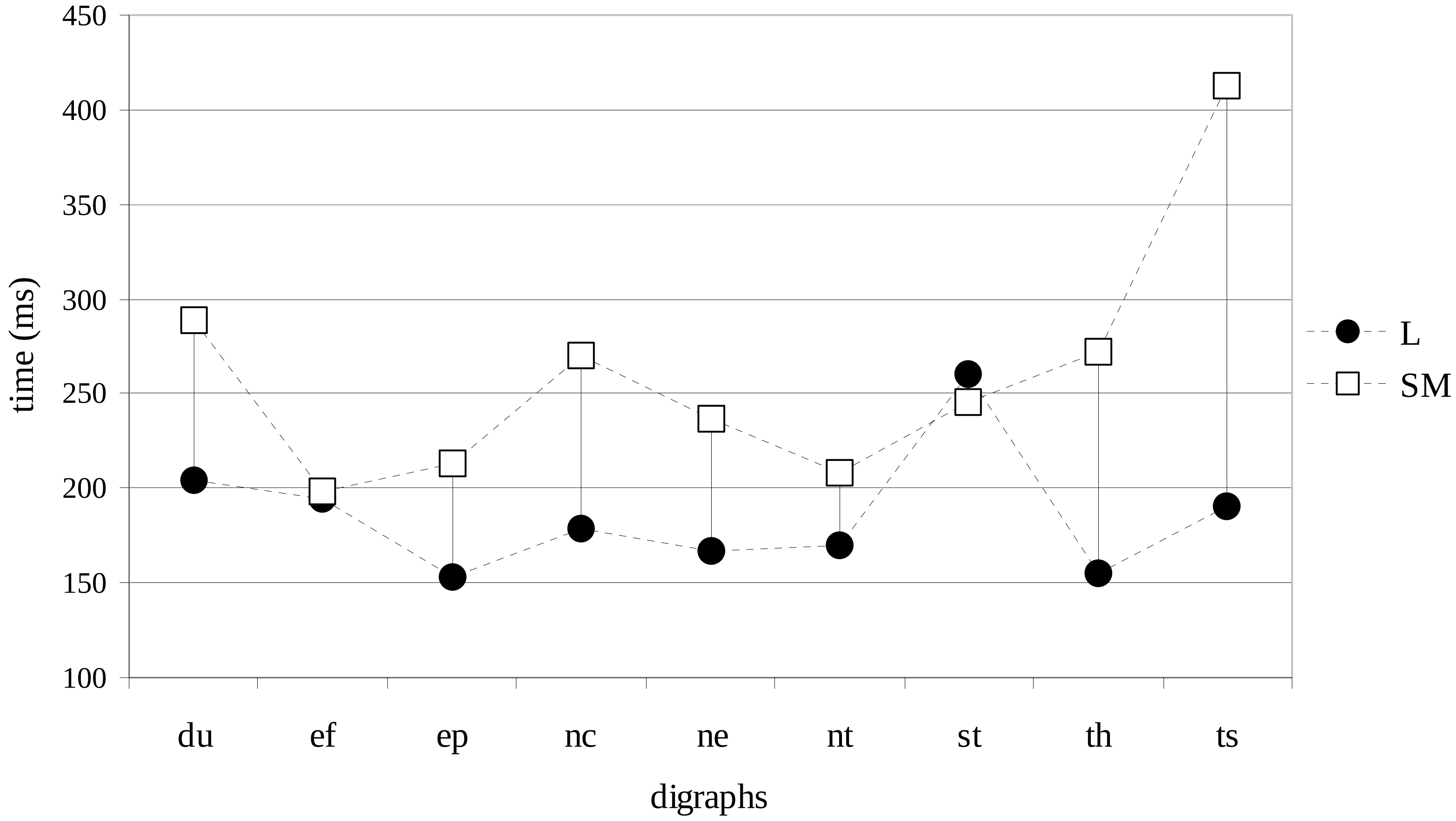

Fig. A2. *Digraph means from experiment 1 for SM-type IKIs in comparison with corresponding L-type IKI (fast typists).*