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TYPING LETTER STRINGS VARYING IN ORTHOGRAPHIC STRUCTURE *

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Subjects typed six-letter strings varying in orthographic structure. Lexical status, word frequency, position-sensitive log bigram frequency, and regularity of letter sequencing were systematically varied. Cumulative reaction times (RTs) of the keystrokes were adequately described by a linear function of letter position in the test string. Overall, words were typed faster than nonwords, and regular strings faster than irregular strings. Although the effect of log bigram frequency was not significant, this variable interacted with regularity and word frequency. Post hoc analyses of performance on each of the 200 letter strings revealed significant effects of the number of irregularities, log bigram frequency, and log word frequency. Transition times between successive keystrokes were significantly longer for illegal than for legal letter transitions. These results are similar to previous findings on the role of orthographic structure in the perceptual recognition of letter strings and provide a more complete analysis of context effects in typing.

The goal of the present experiment is to evaluate the role of orthographic structure (spelling constraints) in the typing of letter strings. The experiment extends our previous perceptual recognition studies to include a complex performance component. Rather than a simple decision response, subjects are asked to type discontinuous (discrete) presentations of the letter strings as quickly and accurately as possible.

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One central question is whether the typing task will provide results consistent with what might be expected on the basis of our earlier work. In addition, the current study should allow a better understanding of typing behavior and how orthographic structure influences typing performance.

Previous studies of orthographic structure in typing limited their analyses to position-insensitive frequency (Grudin and Larochelle 1982; Larochelle 1983; Terzuolo and Viviani 1980). Massaro et al. (1980) found that position-sensitive counts give consistently better descriptions of perceptual recognition performance than do position-insensitive counts. In addition to assessing the contribution of position-insensitive frequency, the current study evaluates the contributions of both position-sensitive frequency and regularity measures of orthographic structure.

Venezky and Massaro (1979), Massaro et al. (1979) and Massaro et al. (1980) distinguish between two broad categories of orthographic structure: *statistical redundancy* and *rule-governed regularity*. The first category includes all descriptions derived solely from the frequency of letters and letter sequences in written texts. The second category includes all descriptions derived from the phonological constraints in English and scribal conventions for the sequences of letters in English words. Although these two descriptions are highly correlated in written English, it is possible to create letter strings that allow the descriptions to be orthogonally varied. Given these strings as test items, perceptual recognition tasks have been carried out to decide which general category seemed to reflect the manner in which readers store and utilize knowledge of orthographic structure.

Massaro et al. (1979; 1980) contrasted specific statistical-redundancy descriptions with specific rule-governed descriptions by comparing letter strings that varied orthogonally with respect to these descriptions. The statistical redundancy measures were summed token single-letter frequency, bigram frequency, and log bigram frequency. The rule-governed regularity measures were various sets of rules based on phonological and scribal constraints. In a typical experiment, six-letter words and anagrams of these words were used as test items. The anagrams were selected to give letter strings which represented the four combinations formed by a factorial arrangement of high or low frequency and regular or irregular. In a series of experiments utilizing a target-search task, subjects were asked to indicate whether or not a target letter was present in these letter strings. Both accuracy and reaction-time measures indicated some psychological reality for both frequency and the regularity descriptions of orthographic structure.

Consider an experiment carried out by Massaro et al. (1981). Some examples of the words and their respective anagrams are presented in fig. 1. *Period* has a high word frequency while *coined* has a low word frequency. The letter string *rodipe* is a regular-high anagram of the word *period*, and *nidcoe* is a regular-low anagram of *coined*. The number in each cell gives the average summed-positional log bigram frequency for the items of that class. For example, the irregular-high anagrams of high frequency words have an average count of 11.625. Forty high-frequency and 40 low-frequency words were selected along with four anagrams of each word. The anagrams were selected so that they formed a factorial arrangement of high and low summed-positional log bigram frequency and of being orthographically regular and irregular.

These six-letter words and their anagrams were used as test stimuli in a target-search task. The test string was presented for a short duration followed by a masking stimulus and the target letter. Subjects responded yes or no whether the target letter was present in the test

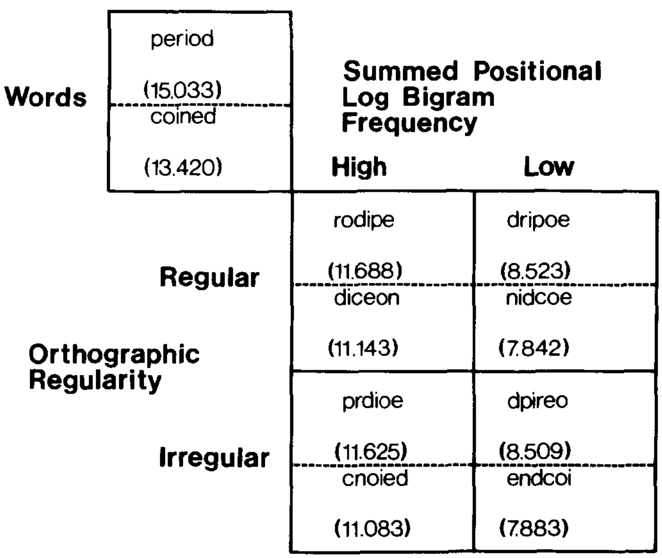

Fig. 1. Examples of the test words and their corresponding anagrams.

string. There was an advantage of words over regular-high anagrams and an advantage for regular over irregular anagrams. There was also an advantage for high-frequency words over low-frequency words. Word frequency of the items from which the anagrams were derived did not have a significant effect on perceptual recognition of the anagrams. Post hoc correlations with performance accuracy on each of the test strings gave significant effects of position-sensitive log bigram frequency and regularity.

The results of these studies provided evidence for the utilization of higher-order knowledge in the perceptual processing of letter strings. Lexical status, orthographic regularity, and frequency appear to be important components of the higher-order knowledge that is used. The goal of the present investigation was to assess the role of these variables in the typing of letter strings. The experiment used 200 of the 400 six-letter strings used in the Massaro et al. (1981) study. The design of the items in the study was equivalent to that depicted in fig. 1. On each trial, one of the six-letter strings was presented and the subjects typed the string as accurately and as quickly as possible. Accuracy and reaction times (RTs) of the successive keystrokes were recorded. The results were analyzed to provide an evaluation of the contribution of various aspects of orthographic structure to typing behavior. In addition, we looked at the contribution of certain motor requirements in the execution of the response.

There is good evidence that the contextual influences in typing are primarily sublexical and are in close proximity to the letter being typed. Shaffer (1973, 1978) evaluated various contextual influences in continuous typing by manipulating the amount of upcoming text exposed during typing. His typist was slowed down when the preview of text was reduced below eight symbols. Although typing random letters or an unknown language slowed down typing, performance with random words was about equivalent to grammatical text. Shaffer also found that certain words such as *and* or *the* have relatively invariant latency profiles across different sentence contexts. In general, the latency profiles for letter combinations were dependent on the context in which they occur. Gentner (1983) measured the influence to extend two letters to the left and one to the right. Thus, most of the contextual influences in typing appear to be contained in a relatively small window of information surrounding the letter being typed.

Previous studies have compared typing of words, pseudowords, and nonwords. Sternberg et al. (1978a) found an advantage of words over pseudowords. Grudin and Larochelle (1982), on the other hand, recorded no difference between words and pseudowords. The latter study equated for position-insensitive bigram frequency across the two classes of items, whereas the previous study did not. Grudin and Larochelle (1982) also found a significant advantage of pseudowords over nonwords, which differed with respect to bigram frequency. The differences that were observed, however, might have been due to position-sensitive frequency or orthographic regularity rather than position-insensitive bigram frequency. The present study extends these earlier studies by determining to what extent various measures of orthographic structure can account for the differences observed with these classes of items.

A long series of studies has demonstrated that increases in frequency (statistical redundancy) decreases errors and interstroke intervals in typing (Fendrick 1937; Shaffer and Hardwick 1970). MacNeilage (1964) found that subjects tended to make more errors on infrequent letter sequences. The strongest evidence for bigram frequency is in the study of Terzuolo and Viviani (1980), who found roughly linear increases in interstroke times with decreases in log bigram frequency in continuous typing. One limitation in these studies involves the confounding of bigram frequency with the nature of the motor response. High frequency bigrams tend to occur on opposite sides of the keyboard and thus are typed by opposite hands. A few studies controlled for this possible confounding. Using a discontinuous typing task, Sternberg et al. (1978a) found no effect of bigram frequency within the class of words or within the class of nonwords. Fox and Stansfield (1964) found a similar result in the continuous typing of text. The one positive finding while controlling for response factors comes from Grudin and Larochelle (1982), who observed a small effect of bigram frequency when typists transcribed a magazine article. The small or negative findings with respect to frequency might be due to the fact that previous studies only evaluated position-independent counts, such as those given by Mayzner and Tresselt (1965). The current study extends these earlier studies by also evaluating position-sensitive frequency counts and separating, as much as possible, frequency and regularity measures of orthographic structure.

The distinction between frequency and regularity measures of orthographic structure might help resolve some of the theoretical interpretations offered to explain frequency effects. It seems reasonable to explain frequency effects in terms of either perceptual-memory or motor processes in typing. Frequency or familiarity might facilitate perception and memory of letter strings (Massaro 1980) or speed up motor programs (Grudin and Larochelle 1982; Terzuolo and Viviani 1980). On the other hand, one might argue that regularity should not influence the execution of motor programs. The execution should be primarily dependent on the physical aspects of typing sequence and the amount of previous practice with the sequence. Thus, regularity might provide a technique to assess perceptual-memory contributions in typing without a possible confounding of motor processes.

Method

Subjects

Seven female *S*s were recruited from the University of Wisconsin community. Although no formal evaluation of their typing speed was made, all *S*s claimed to type at least 40 words per minute. All typists used the standard key to finger assignments. They were paid $20 for participation for about 90 minutes per day for 5 days.

Stimuli and apparatus

A sample of high-frequency words was obtained from a list of all six-letter words from Kučera and Francis (1967), subject to the constraints that the words had a frequency greater than or equal to 50, were not proper nouns, and did not have repeated letters. A similar list of words with a frequency of exactly three was used to obtain low-frequency words. For each word in these two lists, all possible 720 anagrams were generated and each of their summed-positional log bigram frequencies was calculated. The bigram frequencies were based on counts given by Massaro et al. (1980), which were derived from the Kučera and Francis (1967) word list.

Twenty high-frequency and twenty low-frequency words were selected along with four anagrams of each word. The anagrams were selected so that they formed a factorial arrangement of high and low summed position-dependent log bigram frequency and of being orthographically regular and irregular. Orthographic regularity was manipulated in the same manner as in previous experiments (Massaro et al. 1979, 1980). The rules for counting the number of irregularities are given in Massaro et al. (1981). Given these rules, it was possible to equate the number of irregularities for anagrams that differed in log bigram frequency. Consider the test word *person*. The regular high and regular low anagrams (*seporn* and *resnop*) do not have any irregularities. The irregular high and irregular low anagrams (*oprnes* and *pnsero*) have two irregularities each. The 200 stimulus items are presented in the Appendix along with the average summed position-dependent log bigram frequency for each class of items. This design provides an orthogonal contrast between frequency and regularity descriptions of orthographic structure (cf. Massaro et al. 1979, 1980).

Procedure

*S*s were instructed to type the six-letter strings presented one at a time on a CRT in front of the *S*. The *S* began a session by hitting the space bar. After a variable delay of between 400 and 600 msec, an item was displayed. The *S* typed the six letters of the item followed by pressing the space bar "as quickly as possible without error". The item remained on the display until the *S* pressed the space bar. The next item followed after a variable delay of 400 to 600 msec. An experimental session consisted of one presentation of each of the 200 stimulus items. Item order was randomized individually for each session. Each *S* was tested for ten experimental sessions. Usually, two experimental sessions were completed each day with a short rest break between sessions. Up to four *S*s could be tested in parallel in separate rooms.

The visual displays were generated by a DEC LSI-11 computer under software control and presented on Tektronix Monitor 604 oscilloscopes (Taylor et al. 1978a, 1978b). The alphabet consisted of lower case letters without serifs resembling the type font Univers 55 (cf. Taylor et al. 1978a, 1978b). There was no visible space between adjacent dots making up a letter. For an observer seated comfortably at an experimental station, the six-letter displays subtended about 1.9 degrees of visual angle horizontally and the distance from the top of an ascender to the bottom of a descender was about 0.4 degree.

The keyboards were the standard Universal QWERTY layout and were manufactured by Data Electronics. An eighty gram force was the minimum required to effect a keystroke.

Results and discussion

Factorial design

Two analyses of variance were performed on the accuracy scores and the reaction times for correct responses. In the first analysis, word frequency, type of test letter string, and *S*s were factors. In the second analysis, the word data were eliminated and regularity and bigram frequency were added as factors in the design.

A response was scored as correct only if the *S* typed the six-letter item and the space bar in the appropriate order and without omissions and intrusions. *S*s responded correctly on 87 percent of the trials, but there were no significant effects of the independent variables on response accuracy.

Reaction times (RTs) were computed from correct trials only. In the first analysis, cumulative mean RTs were calculated for each *S*, type of test letter string, word frequency, and the seven keystrokes to each test item. In this case, the first RT corresponds to the time between the onset of the display item and the onset of the first key, the second RT corresponds to the time between the display onset and the second key, and so on. There were roughly 174 observations contributing to each mean RT for each condition for each *S*. Fig. 2 presents the cumulative RTs for words, regular items, and irrregular items as a function of key position. As expected, cumulative RTs increased systematically with increases in key position, $F(6,36) = 158.6$, $p < 0.001$. Furthermore, letter string type had a significant influence on RT, $F(4,24) = 32.5$, $p < 0.001$. The average cumulative RT was lowest for words, intermediate for irregular items, and highest for irregular items. Words were typed about 9% more quickly than were regular-high anagrams.

The second analysis was identical to the first except that the word data were eliminated and regularity and bigram frequency were added as factors in place of the factor type of test letter string. The RTs to regular strings averaged about 8.5% shorter than those to irregular strings, $F(1,6) = 35.4$, $p < 0.001$. Although there was no significant effect of log bigram frequency, $F < 1$, a significant interaction of regularity and log bigram frequency, $F(1,6) = 11.8$, $p < 0.025$, reflected a larger 3% effect of regularity for letter strings low in log bigram frequency. The amount of variance accounted for by regularity was 31 times larger than the variance accounted for by both log bigram frequency and the interaction of log bigram frequency and regularity. Based on the

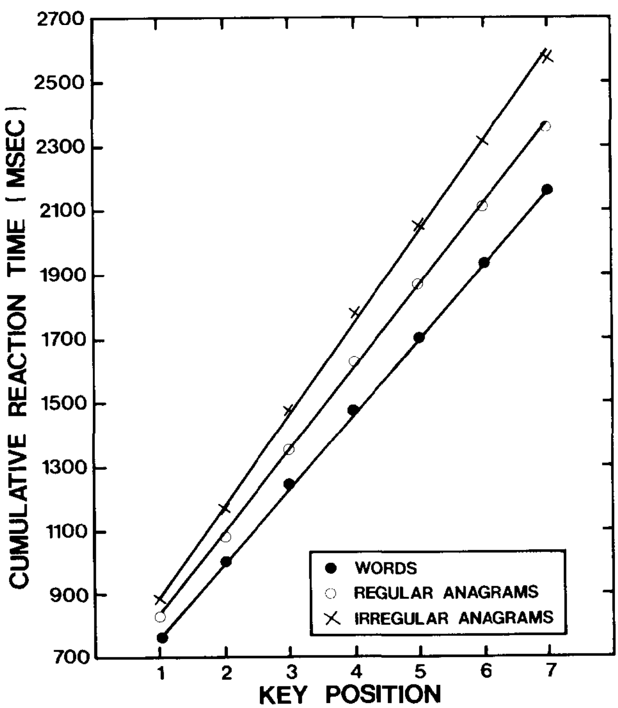

Fig. 2. Average predicted (line) and observed (points) cumulative RT for words, regular, and irregular displays as a function of key position.

factorial design, regularity and not frequency appears to be the critical variable in the task.

The interaction between word frequency and type of test letter string, $F(4,24) = 7.4$, $p < 0.001$, reflected a significant 1.9% RT advantage for the high frequency words but no advantage for the anagrams derived from high frequency words. For the anagram strings, the interaction of word frequency and bigram frequency, $F(1,6) = 25.9$, $p < 0.001$, reflects the smaller RTs when log bigram frequency and word frequency were both high or both low relative to the case when there was a mismatch between these two variables. This interaction is especially surprising given that the words themselves were not included in the analysis. Word frequency in this case simply refers to whether the anagram was derived from a high or low frequency word. Log bigram frequency was not crossed with word frequency for the word items.

It should be noted that identical results were obtained when the analyses of variance were repeated using items rather than *S*s as the measure of error variance.

To assess the contribution of practice in the task and with the 200 test strings, average RTs were computed for each of five pairs of the ten sessions. The RTs decreased by 11.6% across the five pairs of sessions, $F(4,24) = 17.5$, $p < 0.001$. The effects of orthographic structure appear to be relatively consistent across the course of the study. The overall difference between the words and irregular-low anagrams was about 18 percent of the average cumulative RT in the first pair of test sessions and about 17 percent in the fifth pair. The analogous difference between regular and irregular anagrams was 7 and 8 percent. The 12 percent difference between the words and regular-high anagrams in the first pair of test sessions decreased to 8 percent in the fifth pair of test sessions. These results substantiate the idea that the role of orthographic structure remains relatively constant with experience in the experimental task.

Linear functions

As can be seen in fig. 2, the increase in RT as a function of key position appeared to be highly linear. Therefore, a linear function of the form

$$\mathrm{RT} = a + bn$$

where n was equal to the key position, was fit to the cumulative RTs for each S for each display type and word frequency. Fig. 2 also presents the predicted linear functions for the observed cumulative RTs of the words, regular, and irregular test items.

Before using the intercept and slope values as measures of performance, it is important to assess the degree to which the cumulative RTs can be described by linear functions. The absolute deviations between the predicted and observed values were derived and an average deviation was computed for each of the 10 functions for each of the seven *S*s. The average deviations were used as dependent variables in two analyses of variance with the same designs as those described previously. Table 1 gives the means of the intercepts, slopes, and absolute deviations of the linear functions for each S. The means for each S were computed by averaging across the 10 (display type × word frequency) conditions for each S. The linear functions appear to provide a reasonably good description of the cumulative RTs of each S. The mean absolute deviation of 15.9

Table 1
Means of the intercepts, slopes, and absolute deviations for linear functions of the cumulative RTs for each of the seven subjects [a].

Subject	Intercept	Slope	Absolute deviation
1	413	332	9.1
2	572	338	15.4
3	897	234	33.7
4	645	231	12.1
5	421	278	17.2
6	503	217	6.9
7	656	204	16.8
Group mean	587	262	15.9

[a] The means for each subject were computed by averaging across the 10 (display type × word frequency) conditions for each subject.

msec is less than one percent of the average cumulative RT of 1635 msec.

With respect to letter string type, the goodness-of-fit of the linear function decreased with decreases in orthographic structure, $F(4,24) = 1.56$, $p < 0.025$. Table 2 shows that the absolute deviations are positively correlated with the intercept and slope values. This correlation is much stronger than what might be expected from a proportional decrease in absolute deviations with decreases in cumulative RTs. As an example, the

Table 2
Average intercept values, slope values, and absolute deviations of linear functions of the cumulative RTs as a function of display type and word frequency.

Display type	Word	R-H	R-L	I-H	I-L	Average
	Intercept values (msec)					
Word frequency						
High	539	586	572	605	653	590
Low	540	609	653	598	598	581
Average	539	597	568	601	625	586
	Slope values (msec)					
High	229	255	259	279	282	260
Low	236	257	253	289	284	264
Average	233	256	256	284	283	262
	Absolute deviations (msec)					
High	7.9	17.2	11.1	18.4	21.0	15
Low	9.6	16.0	15.2	19.7	22.9	16
Average	8.7	16.6	13.2	19.0	21.9	15

average cumulative RT for words was 91 percent of that for regular high anagrams whereas the analogous proportion was 52 percent for the absolute deviation. This result provides some suggestion that violations of orthographic structure disrupt some underlying linear process responsible for keystrokes to well-structured strings. Even so, the cumulative RTs to all of the items appear to be adequately described by a linear process.

The intercept values *a* and the slope values *b* were treated as dependent variables in analyses of variance. The intercepts of the linear functions tended to decrease with increasing orthographic structure, $F(4,24) = 9.7$, $p < 0.001$. Intercepts averaged 58 msec shorter for words than for regular-high anagrams. Intercepts for regular anagrams were 31 msec shorter than those for irregular anagrams. Although the main effects of bigram frequency and word frequency on the intercept values were not significant for the four types of anagrams, these variables interacted with regularity and with each other. Table 3 presents the mean intercept values for these three interactions. The advantage of regular over irregular strings was limited to those of low bigram frequency $F(1,6) = 17.7$, $p < 0.01$, or equivalently, bigram frequency had positive effects for irregular items and negative effects for regular items. The effect of regularity was also much larger for anagrams derived from words of high word frequency than for anagrams derived from words of low word frequency, $F(1,6) = 18.3$, $p < 0.01$. Finally, log bigram frequency had positive effects on anagrams derived from high frequency words and negative effects on anagrams derived from low frequency words, $F(1,6) = 12.4$, $p < 0.025$.

Fig. 2 shows that slopes of the linear functions tended to be systematically smaller for word items and for regular anagrams, $F(4,24) = 39.4$. The slopes averaged 23 msec less for words than for regular items and 28 msec less for regular than for irregular anagrams. There were no main effects of word frequency or bigram frequency on the slope values. The interaction of word frequency and bigram frequency on the slope

Table 3
The interactions of regularity, bigram frequency, and word frequency on the intercepts of linear functions fit to the cumulative RTs.

	High	Low
	Bigram frequency	
Regularity		
Regular	597	568
Irregular	601	625
	Word frequency	
Regularity		
Regular	579	586
Irregular	629	598
	Word frequency	
Bigram frequency		
High	595	603
Low	613	581

values for the anagrams indicated that bigram frequency had a positive 3 msec effect for anagrams derived from high frequency words but a negative 4 msec effect for anagrams derived from low frequency words, $F(1,6) = 11.4$, $p < 0.025$.

Previous studies have found longer interstroke intervals in the middle of the item being typed (Larochelle 1983; Ostry 1983). These results seem to occur in both discontinuous and continuous typing (Ostry 1983) and with words, pseudowords, and nonwords (Larochelle 1983). The results also hold in immediate and delayed discontinuous typing and with different instructions (Ostry 1983). Ostry (1983) suggested that the slowing of interstroke intervals over the first three or four letters in an item might be a rise time effect in the initiation of a typing sequence. In contrast to these results, the interstroke intervals in the present study were highly constant across serial position. One possible difference to account for the discrepancy is that our *S*s always typed six-letter items, whereas previous studies used test items with different word lengths. Using a fixed length might have encouraged a more constant rhythm in the typing of the letter sequence.

Item analyses

The factorial design is limited in terms of providing a quantitative assessment of the importance of frequency and regularity measures of orthographic structure. The present design contrasted just one frequency measure against just one regularity measure. Therefore, post hoc item analyses were carried out to provide an analysis of a range of descriptions of orthographic structure. The independent variables used in this analysis included a number of measures based on frequency counts for letters, *n*-grams, and words, in addition to a few quantitative measures based on orthographic rules. The dependent measures were the seven cumulative RTs for the seven successive responses, the six inter-response times (interstroke intervals) representing the times between successive responses, and the five I2RTs defined as the times between every other keystroke for each of the 200 six-letter test items. These measures were obtained for each of the 200 test items by averaging across *S*s and across all experimental sessions. This gives a total of about 70 observations (10 replications × 7 *S*s) minus error trials to each datum.

While the effects of frequency seem to be psychologically real, it is not necessary that the mental representations of frequency directly reflect the frequency of objective counts. One alternative scale that has been successful in other research is a logarithmic scale. Not only are there some data to suggest the possibility of a logarithmic representation (Massaro et al. 1980; Solomon and Postman 1952; Travers and Olivier 1978; Taylor 1977), but also a logarithmic representation is consistent with recent studies of number representation (Shepard and Podgorny 1978) and with many other psychological scales. Therefore, we computed all of the frequency measures based upon both linear frequencies and log frequencies. Since counts were sometimes zero, a count of zero was defined as one.

Position-insensitive frequency measures

The token frequency counts given by Solso and King (1976) and Solso and Juel (1980) were used to assess the contribution of overall frequency of occurrence in written language. The source for these counts was the Kučera and Francis (1967) word corpus. For each test item, a summed count was determined by summing the appropriate counts across all serial positions of the test item. For the log counts, the logs were taken before the counts were summed across the serial positions. These summed single letter and bigram linear and log counts were correlated with the cumulative RT to each of the 200 items. Position-insensitive single-letter frequency correlated −0.254 with the total cumulative RT. The analogous log count correlation was −0.309. The linear and log bigram count correlations were −0.228 and −0.411, respectively. Although all of these correlations are statistically significant, the amount of variance accounted for is relatively small. A multiple correlation treating these four counts as independent variables accounted for 19.1% of the variance. Type counts gave essentially equivalent results.

Position-sensitive frequency measures

The source of the frequency measures is contained in Massaro et al. (1980) and is based on the word corpus compiled by Kučera and Francis (1967). A position-dependent count was obtained for each *n*-gram (single-letter, bigram, and trigram) at the position; it occurred in words of a given length. The counts were token counts based upon the total number of occurrences of the words containing the *n*-gram. The single-letter tables and bigram tables for word lengths 3 through 7 are presented in Massaro et al. (1980).

Summed single letter, bigram, and trigram log and linear counts of each of the 200 test items were correlated with the cumulative RTs. Table 4 presents the correlations across the seven key positions. The significant negative correlations show that RTs decreased with increasing frequency counts of the letter strings. The six frequency measures gave reasonably similar descriptions of performance. This is not surprising in that log counts correlated between 0.73 and 0.79 with linear counts and the three kinds of counts correlated with each other (cf. table 5). As can be seen in table 4, correlations

Table 4
Correlations of summed single letter, bigram, and trigram linear and log counts of each of the 200 test items with cumulative RT across the seven key positions.

Variable	Key position						
	1	2	3	4	5	6	7
Single letter							
Linear	−0.18	−0.21	−0.22	−0.23	−0.25	−0.28	−0.31
Log	−0.31	−0.37	−0.39	−0.42	−0.44	−0.47	−0.51
Bigram							
Linear	−0.25	−0.27	−0.29	−0.35	−0.37	−0.38	−0.40
Log	−0.36	−0.39	−0.41	−0.47	−0.48	−0.51	−0.52
Trigram							
Linear	−0.30	−0.32	−0.33	−0.40	−0.41	−0.42	−0.43
Log	−0.38	−0.39	−0.42	−0.50	−0.50	−0.52	−0.53

of RTs with single letter linear counts appear to be relatively smaller than with the other five kinds of counts. Log counts tend to do better than linear counts and the correlations are better with increasing unit size. In addition, there is a strong effect of serial position of the keystroke with the correlations increasing with increasing position.

In addition to the cumulative RTs, two interstroke times were treated as variables in the post hoc correlations. First, six interstroke times were defined in terms of the times between successive keystrokes. Second, five interstroke intervals were defined in terms of the times between every other keystroke. These response times were correlated with frequency counts of letter units at particular serial positions in the test items. For example, it is possible to assess the correlation of the single letter positional frequency with the time required to press the appropriate key. For a letter in the first position, the response time would be the RT measured *from* the onset of the stimulus. For second position, the response time would be the interstroke time between the first and second keystrokes, and so on. For bigrams, the correlation is taken between the frequency of a bigram at two letter positions and the interstroke time between those two positions. For trigrams the correlation is computed between the trigram and the interstroke time between the first and third keystrokes.

Table 6 presents correlations between the response times and single letter, bigram, and trigram linear and log counts. As can be seen in the table, the frequency measures are significantly and negatively correlated with the response times. Log counts do better than linear counts and the correlations are more negative for units of larger size. The most impressive correlations are between log bigram frequency and the interstroke times in initial and final positions.

Previous research has shown that regularity, bigram frequency, and lexical status are important determinants of perceptual recognition of letter strings. In the present study, the total cumulative RT to each item correlated 0.56 with the number of irregularities, −0.52 with summed log bigram frequency, and −0.46 with log word frequency. A multiple regression analysis with these three variables revealed that regularity accounted for 17 percent of the variance beyond that accounted by the two frequency variables. The three variables together accounted for 47 percent of the total variance. Log word

Table 5
Cross correlations of single letter, bigram, and trigram linear and log counts.

	Single letter		Bigram		Trigram	
	Linear	Log	Linear	Log	Linear	Log
Single letter						
Linear	–					
Log	0.76	–				
Bigram						
Linear	0.69	0.53	–			
Log	0.60	0.65	0.73	–		
Trigram						
Linear	0.34	0.34	0.71	0.64	–	
Log	0.47	0.43	0.72	0.80	0.79	–

frequency accounted for just one percent of the variance beyond that accounted for by summed log bigram frequency and regularity. The intercept value in the multiple regression was 2615 msec and the slope values were 101 msec for the number of irregularities, −27 msec for summed log bigram frequency, and −37 msec for log word frequency.

Regularity measures

The quantitative measure of the regularity of each of the 200 stimulus items was the simple count of the number of orthographic irregularities defined by the rules given by Massaro et al. (1981). This measure correlated 0.56 with the total cumulative RT.

The 200 items were partitioned into various classes in order to assess influences of orthographic regularity. In the first analysis, the rules of orthographic regularity were used to define legal or illegal transitions between adjacent letters in the 80 irregular items. The legality of a transition was determined by analyzing the item from left to right. As an example, the item *obndey* has a violation between positions 3 and 4. The transition between positions 2 and 3 is legal since a syllable boundary is possible. However, given a syllable boundary at positions 2–3, *nd* would be illegal for the initial segment of a new syllable. For each *S*, the interstroke interval between successive keystrokes was computed for both legal and illegal transitions at each letter position. These were used as dependent variables in an analysis of variance with letter positions, legal–illegal transition, and *S*s as factors.

The mean interstroke intervals as a function of illegal or legal transitions and letter positions are presented in table 7. The interstroke intervals were longer for illegal than for legal transitions, $F(1,24) = 20.9$, $p < 0.001$, especially at the early and late letter

Table 6
Correlations of response times with frequency measures as a function of letter position(s). See text for explanation.

	Letter position(s)					
	1	2	3	4	5	6
Single letter						
Linear	−0.37	−0.42	−0.26	−0.27	−0.11	−0.27
Log	−0.40	−0.49	−0.30	−0.25	−0.23	−0.38
	1–2	2–3	3–4	4–5	5–6	
Brigram						
Linear	−0.36	−0.40	−0.32	−0.18	−0.21	
Log	−0.60	−0.33	−0.29	−0.18	−0.56	
	1–3	2–4	3–5	4–6		
Trigram						
Linear	−0.40	−0.38	−0.38	−0.26		
Log	−0.48	−0.39	−0.39	−0.43		

positions, $F(4,24) = 4.4$, $p < 0.01$. The average differences between legal and illegal transitions is 34 msec. These results are not simply a restatement of the differences between regular and irregular items since the present analysis is restricted to only the irregular items. The interstroke intervals between letters of irregular items averaged 29 msec longer than those of regular items.

In a second analysis, violations of regularity at positions 1 and 6 in the six-letter words were examined. For each *S* the interstroke interval between adjacent keystrokes was computed for transitions between positions 1 and 2 and for transitions between 5 and 6, respectively. These interstroke intervals were used as dependent variables in an analysis of variance with letter positions, legal–illegal letter occurrences, and *S*s as factors. The interstroke intervals were 22 msec longer for illegal than for legal letter occurrences, $F(1,6) = 55.2$ $p < 0.001$, and this difference did not interact with letter position. This result provides some evidence that legality of letter occurrences in initial and final position is psychologically significant.

Syllable boundaries

A popular idea is that syllable boundaries are critical in the visual processing and phonological encoding of words in reading (Hanson and Rogers 1968; Smith and Spoehr 1974). To test for the contribution of syllable boundaries, we looked at interstroke intervals between successive keystrokes for two-syllable items as a function of whether or not a syllable boundary was present. Given the small number of occurrences of syllable boundaries at early and late positions, it was possible to test for their influence only at response transitions between the second and third and the third and fourth letter. A dictionary was used to determine syllable boundaries for words. For some of the regular anagrams, the location of the syllable boundary was somewhat arbitrary, since it could occur in either of two positions. It was not possible to make consistent decisions about syllable boundaries for irregular items and, therefore, they were not analyzed.

For each *S*, an interstroke interval was computed for transitions across syllable boundaries and for transitions within a syllable. These interstroke intervals were entered into an analysis of variance with display type (words, regular-high, and regular-low), transition position (2–3, 3–4), syllable boundary (yes, no), and *S*s as factors. The interstroke intervals were 12 msec longer for transitions across syllable boundaries than for within syllable transitions, $F(1,6) = 9.46$, $p < 0.025$. As can be seen in table 8, this effect varied between -11 and 28 msec, but the interactions with

Table 7
The average interstroke intervals (msec) to irregular anagrams as a function of whether an illegal or legal transition occurs between two successive letters.

	Letter positions				
	1–2	2–3	3–4	4–5	5–6
Illegal	326	337	319	292	297
Legal	272	304	299	275	252

Table 8
The average interstroke intervals (msec) as a function of letter-string type, letter positions, and whether or not a syllable boundary intervened between two successive letters.

Letter string type	Syllable boundary	Letter positions	
		2–3	3–4
Words	Yes	244	230
	No	236	226
Regular-high	Yes	266	285
	No	277	267
Regular-low	Yes	288	278
	No	260	250

display type and transition position did not reach statistical significance. Given that the effect of syllable boundaries relative to no syllable boundaries was only 6 msec for words and the uncertainty of assigning syllable boundaries to nonwords, very little of a case can be made for the contribution of syllable boundaries in typing the test items.

Ostry and Munhall (1979) evaluated the role of syllable structure in the typing of word strings. Although they (1979) found some differences in interstroke times due to syllable structure, various aspects of orthographic structure were not controlled. Differences due to syllable boundaries could result from frequency of letter combinations since we would expect less frequent letter combinations across rather than with syllables (Massaro et al. 1980). Orthographic constraints are greater within than between syllables. We found only a small effect of syllable boundaries in our word strings and a direct comparison independently varying syllable boundaries and orthographic structure remains to be carried out.

Comparison with perceptual recognition

To evaluate whether the typing task gives similar results to the target search task carried out by Massaro et al. (1981), performance was correlated across the two studies. Massaro et al. (Experiments 3 and 4, 1981) used the same 200 items used in the present typing study. Percentage accuracy was the dependent measure in the Massaro et al. study and the correlation of performance on the 200 individual items was 0.51 across the two experiments. This correlation represents an index of test-retest reliability and thus represents the maximum correlation that can be expected between the accuracy and typing tasks. Accuracy across the 200 items in Experiments 3 and 4 correlated −0.47 and −0.34, respectively, with the total cumulative typing times in the present study. Hence, the two tasks appear to reflect very similar influences of orthographic structure.

Response variable

The central goal of this study was to evaluate the influence of various aspects of orthographic structure on typing speed. Another question of interest is how typing speed varies with the response sequences required by the test items. There is some evidence that typing letter sequences by the same hand is slower than typing letter sequences by alternating between the hands (Larochelle 1983; Ostry 1983; Sternberg et al. 1978b). Two analyses were performed to assess whether successive responses with the same hand were slower than those executed with different hands. The test items were six letters in length, gving a total of five response transitions to analyze. For each transition position, an average interstroke interval was computed for same hand and for alternating hand transitions. There was a 10 msec advantage for typing with alternate hands. In another analysis, the test items were partitioned with respect to the total number of hand transitions needed to type the string. The total cumulative RTs were averaged to evaluate the effect of this variable. There was no systematic effect of the total number of hand transitions. The average total cumulative RTs were 2439, 2372, 2413, 2472, and 2411 msec for 1 through 5 hand transitions respectively.

The correlation between the number of transitions and the total cumulative RT was a nonsignificant 0.061. Given that most of the previous positive findings were obtained with words, the analyses were repeated for each of the 10 classes of items. The correlation was statistically significant only for the class of high-frequency words, $r = -0.534$, $t(18) = 2.679$, $p < 0.02$. The total cumulative RT decreased from 2310 to 2086 msec as the number of transitions increased from 1 to 4 for the high frequency words. Hence, the present study replicates the previous studies and shows that the advantage of alternating hands may be limited to the typing of common or high frequency words. The large effect for the high frequency word items when the number of hand transitions is correlated with the total cumulative RT and the small differences in the interstroke intervals for same and alternating hands might seem paradoxical. However, the total number of hand transitions in a string in discontinuous typing might influence keystrokes that involve both same and alternating hands. Thus, decreasing the number of hand transitions might slow down the typing of both same and alternating hand transitions.

Terzuolo and Viviani (1980) found that interstroke intervals were shorter for pairs of letters typed by both hands than for pairs typed by the same hand. Even so, the difference was decreased significantly if repeated-letter pairs were eliminated from the analysis. For one *S*, the 29 msec difference was decreased to 21 msec. Our letter strings did not contain repeated letters and we observed a 10 msec difference.

Both Ostry (1983) and Larochelle (1983) have studied differences in the typing of letter sequences with the same hand versus alternating hands. The latency of the initial keystroke to the letter sequence and the interstroke intervals are influenced in different ways by this variable. Larochelle (1983) used items 3 to 6 letters in length in a discontinuous typing task. There was about a three second delay between the offset of the test item and the cue to initiate the typing response. The items could either be typed with the same hand or required a strict alternation between the hands. For skilled typists, the initial latencies were 39 msec shorter for the same-hand relative to the alternating-hand items. In contrast, the interstroke intervals averaged 59 msec shorter for the alternating-hand items. For novice typists, similar results were found except that shorter interstroke intervals for the alternating-hand items were not found for the longer word lengths.

Ostry (1983) looked at the differences between hand alternations and hand repetitions in the immediate typing of five-letter words in a discontinuous typing task. The initial latencies preceding a repetition were 17 msec shorter than those preceding an alternation. In contrast, the interstroke times were 45 msec longer for repetitions than for alternations. Interestingly, the absolute advantage of hand alternations for the interstroke times remained constant across a wide range of typing speeds. Thus, although interstroke intervals are shorter preceding a hand alternation, there is an increase in the latency period before the first keystroke of a hand alternation. Ostry (1983) suggested that the bimanual activity may be more complex than unimanual activity even though the bimanual movements may be made more quickly once they are begun.

General discussion

Typing behavior appears to provide an informative index of pre-motor and motor processing of letter strings. Although the typing paradigm contains a response component relative to traditional tachistoscopic tasks, typing responses show similar effects of orthographic structure. Performance in the typing study was highly correlated with accuracy performance in a tachistoscopic perception task. Regularity, frequency, and lexical status of letter strings influence performance in both tachistoscopic and typing tasks. Given that the tachistoscopic task does not contain the motor component involved in typing, the similar effects of orthographic structure in the typing task might be interpreted as resulting from pre-motor processes rather than from motor processes.

Previous studies of typing have relied primarily on position-insensitive frequency as a measure of orthographic structure. In the present study, the post hoc item analyses indicated that position-sensitive frequency provided a more complete account of context effects in typing than did position-insensitive frequency. For example, the correlation of RT with log bigram frequency was -0.41 for position-insensitive counts. Thus, adding position sensitively accounts for 10 percent more of the RT variance. In addition to position-sensitive frequency, rule-governed regularity was shown to be an important influence in typing behavior.

The effects of frequency and regularity can be related to the issue of pre-motor or motor accounts of the effect of orthographic structure. Although frequency might be viewed as having an influence at either stage, it seems most reasonable to interpret the effect of rule-governed regularity at a pre-motor stage of processing in the typing task. It is difficult to imagine how a motor program might be less efficient when typing letter sequences that violate certain rules of regularity in the language. Future studies would be very valuable if they could better isolate pre-motor and motor consequences in typing.

Many studies of typing use a delayed response condition to assess typing processes "uncontaminated by the current perception of new material" (Sternberg et al. 1978b: 118). However, the delayed response does not seem adequate to eliminate perceptual and memory contributions to typing performance. Ostry (1980) had subjects type a word or a nonword either immediately upon its presentation or after a delay of one second. Although the advantage of words was greater in the immediate than in the delayed response condition, there was still a significant word advantage with a response delay. More importantly, the delayed response condition facilitated typing but this facilitation did not extend beyond the first three or four characters in the letter string. Given the limitation of short-term memory, it is not surprising that perceptual and memory processes would be apparent in the typing responses even under delayed typing conditions.

Rumelhart and Norman (1982) provide a simulation model for skilled typing. The simulation begins with word units, which are the output of a perceptual processor. Their model accounts for all of typing behavior as a function of motor and keyboard variables. In its present form, the model is not capable of accounting for the contextual effects of orthographic structure. The assumption of word units would have to be modified to extend the model to account for the typing of nonword letter strings in the present experiment. Of central interest would be how in the model the influences of orthographic structure would be implemented and how these influences would interact with motor and keyboard variables.

Appendix

Table A1
The 200 stimulus items used in the experiment with the average summed position-dependent log bigram frequencies for each stimulus class [a].

Words	Regular high	Regular low	Irregular high	Irregular low
High word frequency items				
almost	olmast	otsalm	aslmot	atsoml
around	anudor	adorun	douanr	onaudr
beyond	dobney	bodnye	obndey	oebndy
coming	cogmin	nicmog	cimngo	cgnomi
during	rignud	rigdun	urindg	gduinr
ground	drugon	nodrug	ourdgn	dnorgu
having	vahign	vinhag	vnghia	hngaiv
market	materk	mekart	atrkem	earmkt
modern	remdon	nemrod	enrmod	orendm
nature	reatun	tearun	atrnue	nrauet
others	esthor	ershot	erosth	hstero
period	rodipe	dripoe	prdioe	dpireo
person	seporn	resnop	oprnes	pnsero
points	notips	snipot	inopst	stpino
result	ruslet	tesrul	uertls	lsrtue
taking	takgin	kitnag	itankg	aginkt
toward	tawdor	darwot	otrdaw	orawtd
turned	drenut	netrud	untrde	uerndt
volume	volmue	vomlue	vmouel	oulmev
walked	dawkel	ledkaw	eakwld	kdewla
15.119	11.429	8.291	11.441	8.282
Low word frequency items				
coined	diceon	nidcoe	cnoied	endcoi
confer	cefnor	cerfon	frneco	efcnor
consul	conlus	scolun	snculo	uslnoc
copied	diecop	pidcoe	eicopd	oedicp
dearth	rhetad	tedhar	ehatrd	adhtre
easing	isagen	aginse	aiengs	gsanei
famine	mifane	neifam	faiemn	fniema
fathom	thamof	mohaft	athomf	ofahtm
forage	gafeor	reafog	reoagf	faegro
gamble	begalm	melbag	eamblg	maeblg
glazes	zagsel	zeslag	aglesz	gszela
gulped	gudpel	pedlug	pldgeu	elupdg
hurdle	hudler	helrud	uhrled	hlderu
jurist	jisurt	jisrut	turisj	surjti
punish	hinsup	siphun	sphinu	pshinu
raving	vignar	vinrag	grvina	ravngi
repaid	riedap	reipad	ariedp	rpeida
scrape	rescap	serpac	prcaes	earscp
slated	lesdat	tedlas	saetld	lesdta
sultan	tanuls	tanlus	unatls	snltau
13.896	10.956	7.759	10.981	7.742

[a] The seven cumulative RTs for each item are available from the author.

References

Fendrick, P., 1937. Hierarchical skills in typewriting. Journal of Educational Psychology 23, 262–278.

Fox, J.G. and R.G. Stansfield, 1964. Digram keying times for typists. Ergometrics 7, 317–320.

Gentner, D.R., 1983. 'Keystroke timing in skilled typing'. In: W.E. Cooper (ed.), Cognitive aspects of skilled typewriting. New York: Springer-Verlag.

Grudin, J.T. and S. Larochelle, 1982. Digraph frequency effects in skilled typing. (CHIP 110) San Diego, CA: University of California.

Hanson, D. and T. Rogers, 1968. 'An exploration of psycholinguistic units in initial reading'. In: K.S. Goodman (ed.), The psycholinguistic nature of the reading process. Detroit, MI: Wayne State University Press.

Kučera, H. and W.N. Francis, 1967. Computational analysis of present-day American English. Providence, RI: Brown University Press.

Larochelle, S., 1983. 'A comparison of skilled and novice performance in discontinuous typing'. In: W.F. Cooper (ed.), Cognitive aspects of skilled typewriting. New York: Springer-Verlag.

MacNeilage, P.F., 1964. Typing errors as clues to serial ordering mechanisms in language behavior. Language and Speech 7, 144–159.

Massaro, D.W., 1980. 'How does orthographic structure facilitate reading?' In: J.F. Kavanagh and R.L. Venezky (eds.), Orthography, reading, and dyslexia. Baltimore, MD: University Park Press.

Massaro, D.W., J.E. Jastrzembski and P.A. Lucas, 1981. 'Frequency, orthographic regularity, and lexical status in letter and word perception'. In: G.A. Bower (ed.), The psychology of learning and motivation, Vol. 15. pp. 163–200.

Massaro, D.W., R.L. Venezky and G.A. Taylor, 1979. Orthographic regularity, positional frequency, and visual processing of letter strings. Journal of Experimental Psychology: General 108, 107–124.

Massaro, D.W., G.A. Taylor, R.L. Venezky, J.E. Jastrzembski and P.A. Lucas, 1980. Letter and word perception: orthographic structure and visual processing in reading. Amsterdam: North-Holland.

Mayzner, M.S. and M.E. Tresselt, 1965. Tables of single-letter and digram frequency counts for various word-length and letter-position combinations. Psychonomics Monograph Supplement 1, 13–32.

Ostry, D.J., 1980. 'Execution-time movement control'. In: G.E. Stelmach and J. Requin (eds.), Tutorials in motor behavior. Amsterdam: North-Holland.

Ostry, D.J., 1983. 'Determinants of interkey times in typing'. In: W.E. Cooper (ed.), Cognitive aspects of skilled typewriting. New York: Springer-Verlag.

Ostry, D.J. and K.G. Munhall, 1979. Levels of organization in the timing of motor sequences. Paper presented at Psychonomic Society, Phoenix.

Rumelhart, D.E. and D.A. Norman, 1982. Simulating a skilled typist: a study of cognitive-motor performance. Cognitive Science 6, 1–36.

Shaffer, I.H., 1973. 'Latency mechanisms in transcription'. In: S. Kornblum (ed.), Attention and performance, Vol. 4. London: Academic Press.

Shaffer, I.H., 1978. Timing in the motor programming in typing. Quarterly Journal of Experimental Psychology 30, 333–345.

Shaffer, I.H. and J. Hardwick, 1970. The basis of transcription skill. Journal of Experimental Psychology 84, 424–440.

Shepard, R.N. and P. Podgorny, 1978. 'Cognitive processes that resemble perceptual processes'. In: W.K. Estes (ed.), Handbook of learning and cognitive processes: human information processing, Vol. 5. Hillsdale, NJ: Erlbaum.

Smith, E.E. and K.T. Spoehr, 1974. 'The perception of printed English: a theoretical perspective'. In: B.H. Kantowitz (ed.), Human information processing: tutorials in performance and cognition. Potomac, MD: Erlbaum Press.

Solomon, R.L. and L. Postman, 1952. Frequency of usage as a determinant of recognition thresholds for words. Journal of Experimental Psychology 43, 195–201.

Solso, R.L. and C.L. Juel 1980. Positional frequency and versatility of bigrams for two- through nine-letter English words. Behavior Research Methods & Instrumentation 12, 297–343.

Solso, R.L. and J.F. King, 1976. Frequency and versatility of letters in the English language. Behavior Research Methods & Instrumentation 8, 283–286.

Sternberg, S., R.L. Knoll and C.E. Wright, 1978a. The timing of rapid movement sequences in typewriting. Paper presented at Psychonomic Society meeting, San Antonio, Texas.

Sternberg, S., S. Monsell, R.L. Knoll and C.E. Wright, 1978b. 'The latency and duration of rapid movement sequences: comparisons of speech and typewriting'. In: G.E. Stelmach (ed.), Information processing in motor control and learning. New York: Academic Press.

Taylor, G.A., 1977. The contribution of orthographic structure to the perception of letter strings. Unpublished doctoral dissertation, University of Kansas.

Taylor, G.A., D. Klitzke and D.W. Massaro, 1978a. A visual display system for reading and visual perception research. Behavior Research Methods & Instrumentation 10, 148–153.

Taylor, G.A., D. Klitzke and D.W. Massaro, 1978b. Correlations in software character generation. Behavior Methods & Instrumentation 10, 787–788.

Terzuolo, C.A. and P. Viviani, 1980. Determinants and characteristics of motor patterns used for typing. Neuroscience 5, 1085–1103.

Travers, J.R. and D.G. Olivier, 1978. Pronounceability and statistical 'Englishness' as determinants of letter identification. American Journal of Psychology 91, 523–538.

Venezky, R.L. and D.W. Massaro, 1979. 'The role of orthographic regularity in word regulation'. In: I. Resnick and P. Weaver (eds.), Theory and practice of early reading. Hillsdale, NJ: Erlbaum.