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Orthographic Regularity, Positional Frequency, and Visual Processing of Letter Strings

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SUMMARY

Previous research has demonstrated that familiarity with the orthographic structure within a letter string can facilitate the processing of the component letters. The current research was directed at discovering the psychologically relevant properties of this structure. Two fundamental descriptions were independently varied in the construction of six-letter nonword strings. A probabilistic description based on the frequency of occurrence of letters in each position was factorially combined with a rule-governed description defined in terms of graphemic and phonological constraints. College sophomores and sixth-grade readers were asked to indicate whether or not a predesignated target letter was present in these strings. For both groups of readers, orthographic regularity and summed positional frequency were found to have only a small facilitative effect on reaction time (RT). In contrast, RTs to say "no" increased dramatically with increases in the number of letters in the catch string that were physically similar to the target letter. In another experiment, the letter string was presented for a short duration, followed immediately by masking stimulus and then the target letter. College students indicated whether or not the target was present in the test string. Accuracy of performance was critically dependent on the orthographic regularity and summed positional frequencies of the letters in the test string. No effect of letter similarity was observed. The large differences that were observed between these two tasks were accounted for in terms of the stages of processing that are critical for performance in the tasks.

The processes by which words are recognized during reading have concerned psychologists and educators for almost a century. From Huey (1908/1968) to Gibson and Levin (1975), every major treatise on reading has discussed this issue at length, and generally concluded, as did Huey (1908/1968), that "it is very difficult to draw final conclusions concerning visual perception in reading" (p. 102). At the turn of the century, work on word recognition concentrated on word shape and dominating letters (Woodworth, 1938), using full report of briefly presented words. More recently, word recognition studies have concentrated on the effects of orthographic structure, using paradigms similar to the visual recognition paradigm initiated by Reicher (1969). In this task, a single letter or a letter string is presented for a short period, followed by a visual masking stimulus. The subject is then

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given two alternative letters and indicates which of the alternative letters was presented at an indicated position in the display. The alternatives are selected to eliminate the possibility of a guessing advantage for highly constrained letter strings.

For example, if the subject were shown the display WORD, the alternatives would be _ _ _D and _ _ _K. In this case, knowing that the display was a word and that WOR occurred in the first three positions would not be sufficient information for the subject to choose between D and K in the fourth position, since both alternatives spell words. Performance on this trial would be compared to a letter trial in which D would be presented without context, followed by the alternatives D and K and a nonword trial in which ORWD would be presented followed by the alternatives _ _ _D and _ _ _K. When Reicher initiated the paradigm, he found a 10% advantage for words over nonwords and single letters. This basic result has been replicated by Wheeler (1970), Johnston and McClelland (1973), and Thompson and Massaro (1973). A similar advantage has been found with pseudowords, which are spelled like English words but have no meaning (Aderman & Smith, 1971; Baron & Thurston, 1973). This latter result shows that orthographic structure can contribute to perceptual processing independently of meaning, although the latter may also contribute to the "word" advantage (Juola, Leavitt, & Choe, 1974; Manelis, 1974).

A variation on the Reicher paradigm is the target search paradigm, in which a subject attempts to determine whether or not a target letter (or letters) is present in a test string. Krueger (1970b) presented subjects with a target letter followed by a display of 25 six-letter words or 25 six-letter nonwords. The nonwords were formed by randomly permuting the letters at each serial position in the words. Search time was about 20% faster through word than nonword displays. In another experiment, Krueger (1970b) looked at relative search times for common and rare words and third-order pseudowords. Subjects saw a target letter followed by a display of two six-letter strings. Given an average RT of 1,000 msec, search time was 36 msec faster for common than for rare words while rare words were 48 msec faster than the third-order pseudowords. The pseudowords were in turn 28 msec faster than the nonword strings. In a final study (Krueger, 1970b), highly practiced subjects searched for one, two, or three target letters in word and nonword displays of two six-letter strings. Search time was a linear increasing function of the number of target letters and was faster for word than nonword displays. More important, these two effects were additive, indicating that the word–nonword difference was affecting overall search time at a different processing stage than was the number of target letters. Since it is commonly assumed that the number of target letters influences memory comparison, the advantage of the word strings might be located at the recognition stage of processing.

Gilford and Juola (1976) compared visual search to memory search using word and nonword test items. The nonwords were generated by rearranging (and sometimes replacing) letters in one-syllable words to give pronounceable one-syllable anagrams. There were no significant differences between the two tasks. The RTs increased linearly with increases in the number of letters in the test items and were consistently 40 msec faster to word than nonword displays. Replication of Krueger's (1970b) results using both visual and memory search paradigms, however, produces a conceptual problem with localizing the differences between words and nonwords at the recognition stage of processing. In memory search, the target item was presented 2 sec after the test item whereas the target was presented 2 sec before the test item in visual search. If it is assumed that the advantage of words over nonwords in visual search was due to a more rapid recognition of word than nonword test items, then the target letter must have been recognized faster with word than with nonword test lists in the memory search task. There is no justification for this interpretation, however, since the same single target letter occurred on word and nonword trials and its recognition time should not have been dependent on the nature of the previously presented test item.

In a second series of experiments, Krueger (1970a) had subjects search for a target letter in a single six-letter word or nonword string. The target letter was presented before (visual search), after (memory search), or simultaneously with the test string. The subjects responded about 9% faster for words than nonwords when the target was presented after the display and about 5% faster when the target letter was presented before the display. In the simultaneous presentation, the target letter was centered immediately above the test string or was repeated above each letter in the test string. A 4% word advantage occurred in both variations of this procedure. The only condition that eliminated the word advantage was one in which the letters in the string were arrayed vertically rather than in their standard horizontal arrangement. Krueger's (1970a, 1970b) results offer substantial support for the utilization of orthographic structure in searching for a target letter in test strings. Krueger, Keen, and Rublevich (1974) asked adults and fourth-grade readers to search for a target letter in a list of five six-letter words or nonwords. The RTs were about 10% faster for the words than nonwords and about 3% faster for (third-order) pseudowords than nonwords. These effects did not vary with reading ability.

James and Smith (1970) and Gibson, Tenney, Barron, and Zaslow (1972) failed to find faster search times through pronounceable pseudowords than nonwords, but Krueger (1975) argued that these null effects may be due to the utilization of a less sensitive between-subjects design. Gibson et al. (1972) pointed out, however, that since a single target letter was used, their subjects did not have to recognize each of the test letters but could make decisions on the basis of letter features alone. To test these two explanations, Krueger and Weiss (1976) used a within-subject design and held the target letter constant across trials in a target search task with lists of 30 six-letter items. Subjects searched through word lists about 4% faster than through nonword lists. This significant result supports the commonly accepted idea that comparisons between subjects are insensitive (and inappropriate) in visual information-processing tasks.

Mason (1975) evaluated the contribution of single-letter positional frequency in a letter search task. Good and poor sixth-grade readers indicated whether or not a six-letter string contained a predetermined target letter. Mason (Experiment 2) found that good readers were faster (on both yes and no trials) for strings with high than with low positional frequencies. Poor readers showed no difference. The results support the idea that the time to process the letters in a string is influenced by the likelihood of letters occurring in their more common spatial positions.

In each of the experiments just reviewed, orthographic structure was assumed to facilitate letter search; yet the definitions of this structure were widely disparate, varying from single-letter positional frequency (Mason, 1975) to third-order approximations to English (Krueger et al., 1974) to pronounceability (Gibson et al., 1972). The present study addresses the issue of defining orthographic structure. In doing so, the degree to which the target search task was sensitive to the orthographic structure of letter strings also becomes a relevant question.

A Model for Visual Processing

The conceptual framework for the present research derives from an information-processing stage model (Massaro, 1975a, 1975c; Massaro & Klitzke, 1977). Although this model has received considerable support from a wide variety of information-processing tasks, our purpose in presenting the model here is not to justify it over other models, but to provide a precise framework for both the theoretical hypotheses and the experimental tests of the current research. In the current model, a segment of text is registered as a light pattern on the retina, which stimulates the visual receptors. The

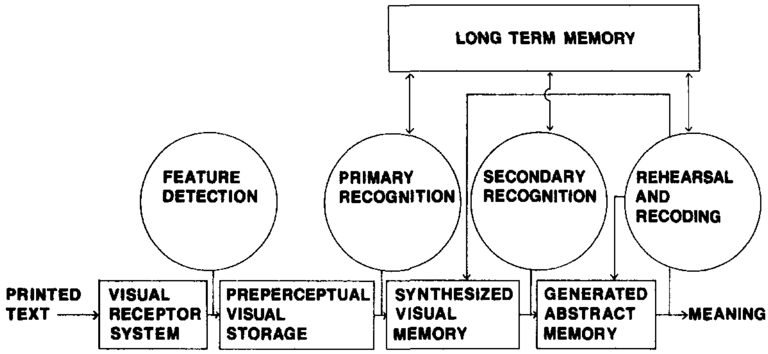

Figure 1. Flow diagram of the processing of printed text.

first process, called feature detection, detects basic letter features, which are transmitted to preperceptual visual storage (see Figure 1). The feature detection process takes time, and it is assumed that different features require different times for detection. For example, the general circular shape of the letters *c* and *o* may be detected before information about about whether or not a gap is present. As the visual features enter preperceptual visual storage, the *primary recognition process* attempts to synthesize these isolated features into a sequence of letters and spaces in synthesized visual memory. To do this, the primary recognition process can utilize information held in long-term memory. For the accomplished reader, this includes a list of features for each letter of the alphabet along with information about the orthographic structure of the language. The primary recognition process utilizes both visual features and information about orthographic structure of the language in its synthesis of the letter string.

The primary recognition process operates on a number of letters in parallel. The visual features that are read out at each spatial location define a set of possible letters for that position. The recognition process chooses from this candidate set the letter alternative that has the best correspondence in terms of visual features. However, the selection of a "best" correspondence can be facilitated by knowledge of orthographic structure. If, for example, *th—m* has been resolved in a letter string and the features available for the third letter match either *c* or *e*, the reader might accept *e* without waiting for further visual information since *thcm* is irregular while *them* is not. The primary recognition process therefore attempts to utilize both the visual information in preperceptual storage and knowledge about the structure of legal letter strings.

The primary recognition process transmits a sequence of recognized letters to synthesized visual memory. The *secondary recognition process* transforms this synthesized visual percept into a meaningful form in generated abstract memory. The secondary recognition process makes this transformation by finding the best match between the letter string and a word in the long-term lexicon. Generated abstract memory corresponds to the short-term or working memory of most information-processing models. In our model, this memory is common to both speech perception and reading. Recoding and rehearsal processes build and maintain semantic and syntactic structures at the level of generated abstract memory. The reader is referred to Massaro (1975b) and Venezky and Massaro (in press) for a more complete description of the model.

Defining Orthographic Structure

Proposals for describing orthographic structure can be classed as either rule governed or frequency governed. The frequency-governed approaches include ordered approximations to English (Miller, Bruner, & Postman, 1954), as well as bigram counts (Herrmann & McLaughlin, 1973) and single letter positional frequencies (Mason, 1975). These descriptions are usually based on counts of letters or letter sequences that occur in words in running text, although word types might also be used (Solso & King, 1976).

Rule-governed approaches, in contrast, attempt to define orthographic structure in terms of the more general linguistic patterns of English spelling. This results in rules or criteria that are based upon both phonological and graphemic constraints, such as the nonoccurrence of initial consonant clusters composed of a voiced consonant followed by a voiceless one, or the use of *ck* rather than *c* or *k* in word final position after a checked vowel spelling. Although no comprehensive set of rules has yet been published, a sketch of the major orthographic constraints is given in Venezky and Massaro (in press). Rule-governed approaches have so far been based on word types rather than word tokens and have yet to incorporate frequency measures, although these are not excluded by definition.

The most important difference between the two approaches is that rule-governed approaches can, at least in theory, generate substrings that do not occur in English words and can eliminate some that do. For example, if *gh* were accepted as a regular spelling for /g/ in word initial position, then the initial spellings, *ghl* and *ghr*, might be generated as regular clusters, even though neither occurs initially in real English words. (Note, however, the parallel with *phr, phl, chl, chr,* and *thr,* all of which do occur in English.)

Although some frequency approaches (e.g., position-sensitive fourth-order approximations) will yield strings similar to those produced by a rule-governed approach, most frequency measures will not. Single-letter positional frequencies, for example, have been offered as descriptions of orthographic structure; yet empirical tests done so far have generally confounded a rule-governed description with a single-letter positional frequency description (Mason, 1975). The positional frequency of a given letter in a letter string is measured by the frequency with which the letter occurs in the same spatial position in words of the same length. The positional frequency of a letter string is the sum of the positional frequencies of each of the individual letters in the string. Positional frequencies can be computed from the tables of Mayzner and Tresselt (1965), which give the total number of occurrences of each letter at each spatial position in a sample of 20,000 words of running text.

Summed positional frequency and rule-governed regularity can be varied independently, however. Consider, for example, some of the permutations of the letters that make up the word *prince*, which has a summed positional frequency of 1,008 according to the Mayzner and Tresselt tables. The strings *picner* and *encrip* are both orthographically regular by a rule-governed description, yet their summed positional frequencies are 1,579 and 426, respectively. Similarly, *rcenip* and *cpnier* are orthographically irregular, but have summed positional frequency counts of 504 and 1,582, respectively. It is not possible to determine from Mason's (1975) results alone whether differences in positional frequency are fortuitous effects of orthographic regularity as defined by phonological and graphemic rules, or if both were responsible for her results.

To evaluate the degree to which summed positional frequency and orthographic regularity are psychologically relevant measures of orthographic structure, we selected letter strings that were high or low in summed positional frequency, and then chose both regular and irregular strings from both of these categories according to an extension of the rules proposed by Venezky and Massaro (in press). (These rules are explained in Appendix A.) If summed positional frequency is a psychologically relevant description of orthographic structure, it should predict performance regardless of regularity. Likewise, if a rule-governed description is psychologically relevant it should predict performance independently of positional frequency. In the present experiments, we independently varied these two descriptions of orthographic structure to provide a direct assessment of the contribution of each to letter processing.

Target Search and Orthographic Structure

A target search task was selected in view of the substantial evidence that orthographic structure facilitates performance in this task. According to the model utilized here, the influence of orthographic structure on performance in the target search task should depend on whether the subject is capable of responding at the level of letter features (i.e., at the feature detection stage) or whole letters (i.e., after the primary recognition stage). If primary recognition must be completed before a decision can be made, we predict a positive effect of orthographic structure in the task; no influence of orthographic structure is predicted if a decision can be initiated at the level of feature detection. At first glance, we might expect that primary recognition must be completed before a decision can be made in the search task. There is some evidence, however, that readers do not have to recognize all of the letters in the test letter string to perform the target search task (Estes, 1975; Massaro & Klitzke, 1977). Consider the case in which the subject is looking for the target letter *b* in the letter strings *cose, peom, deom,* and *delm,* respectively. In all cases the answer is no, but the subject may be able to decide on this answer faster with some of the strings than with others. We assume that recognition of the string is a temporally extended process and that some letter features are resolved before others. There is some evidence that overall letter shape can be resolved and made available to later stages of processing before the letter is completely recognized (Bouma, 1971; Massaro & Schmuller, 1975). In a well-known experiment (Neisser, 1964), subjects searched faster for the uppercase letter Z in a list of curved letters (*O, D, U*) than in a list of linear letters (*T, V, M*). This result indicates that complete letter recognition is not necessary in the target search task. Applying this analysis to the example strings, a subject might be able to respond "no" to the first two example strings very quickly since none of the letters has the same overall ascender shape as the target letter. In contrast, the third and fourth strings will require additional processing time. Other features of the ascending letters of these strings must be resolved to distinguish these letters from the target letter. Accordingly, we might expect that the time to say "no" will be longest for the string with two ascenders, intermediate for the string with one ascender, and shortest for the strings with no ascenders. If subjects are utilizing this processing strategy, then we would not expect a large effect of orthographic structure of the letter string, but rather a significant influence of the number of letters similar to the target letter.

It should be pointed out that for this model the number of letters in the test string of the same overall shape as the target should not be important on target trials. On these trials, the target letter must be completely resolved before a yes response can be made. Therefore, the critical variable on target trials is how quickly the target is recognized rather than the number of letters in the test string that have the same overall shape as the target.

To review, the two central issues addressed by the current research involve an evaluation of the psychological reality of two descriptions of orthographic structure and the degree to which orthographic structure influences performance in the target search task. To evaluate these hypotheses at two levels of reading experience, both adult readers and sixth graders were tested.

Experiment 1

Method

Subjects. Eleven adult subjects who responded to an advertisement posted in the university community participated 1 hr a day for 2 consecutive days. Each subject was paid $4 at the end of the experiment.

Stimulus lists. The stimulus lists were generated from the most frequent 150 six-letter English words in Kucera and Francis (1967). A computer program generated all 720 permutations of the six letters in each word, and computed the summed positional frequency for each permutation from

Mayzner and Tresselt's (1965) counts for the absolute frequency of occurrence of single letters at each position in six-letter words. The program listed the 30 permutations with the highest summed positional frequencies and the 30 permutations with the lowest summed positional frequencies. From these lists one orthographically regular and one orthographically irregular item were chosen from the items with the highest summed positional frequency, using the criteria given in Appendix A. A similar pair of items was chosen from the items that ranked lowest in summed positional frequency. Because of the difficulty of finding orthographically regular items in the low positional frequency group, all of the original 150 words could not be used. The four different types of items could be generated from 80 of the words, giving a total of 320 stimulus items in the experiment. Table B1 of Appendix B lists the words, the 4 permutations that were used in the experiment, and the summed positional frequency of each permutation.

Procedure. The stimulus list of 320 items was divided in half so that the permutations of 40 of the words were in one list and the permutations of the other 40 words were in the other. List 1 had no repeated letters in 37 of the strings and one repeated letter in 3 of the strings. List 2 had at least one repeated letter in each of the 40 strings (see Appendix B). In the experiment proper, each subject was tested on List 1 in the first session and List 2 in the second session each day. List 1 was always given first on Day 1 since this list had only 3 items with repeated letters and it also allowed a direct comparison between the adult's results on Day 1 and the results from the sixth-grade readers in Experiment 2. Each letter string appeared once as a target trial and once as a catch trial. On target trials, the target letter was selected randomly with replacement from the six letters in the test string. On catch trials, the target letter was selected from the remainder of the alphabet. The probability of selecting a given target letter on catch trials was weighted by the frequency of occurrence of that letter in the 320 test strings.

On the first day, the subject was introduced to the visual display and the response panel. To acquaint subjects with the response procedure, they were first given 50 trials of responding "yes" and "no" to the words YES and NO presented on the visual display. All subjects pushed the yes button with their preferred hand. The word remained on until the subject pressed one of the two buttons. Next, the subjects received 50 practice trials with random letter strings. The subject was asked to indicate whether or not a target letter was present in these six-letter strings. Each trial began with a 400-msec presentation of the target letter followed by a 400-msec blank period and then the test letter string. The letter string remained on until the subject pressed one of the two buttons. The interval from the response to the onset of the next trial was 1.5 sec. The subject was instructed to respond "yes" if the target letter appeared at least once in the letter string and "no" otherwise. The subject was also instructed to respond as accurately and quickly as possible. Feedback was given at the end of each practice sequence in an attempt to keep error rates below 3%. This practice session was followed by 320 trials of the experiment proper. After a rest of about 10 min the subject was given a second testing session consisting of 50 practice trials followed by 320 experimental trials. On Day 2 the subject also had two sessions, each with practice trials followed by 320 experimental trials. Each subject was tested for a total of 1,280 trials in the experiment proper, giving roughly 320 observations per subject in each of the four experimental conditions. A 10-min rest break was given between sessions.

Apparatus. The displays were presented on a Beehive video computer terminal under the control of a Harris DC6024/5 computer. A hardware modification permitted the terminal's video to be turned on and off with program-generated control signals. The display strings were loaded into the memory buffer of the terminal with video off and then the video was turned on for the appropriate exposure duration. The Beehive's cathode ray tube (CRT) employs a P4, blue-white phosphor which decays to .1% of maximum luminance in 32 msec. The experiment was conducted in a partially darkened room to enhance image contrast.

All single-letter and letter-string displays were presented in lowercase letters. The Beehive terminal uses a 5×7 dot matrix, 2.5 mm wide and 5 mm high. At the average viewing distance of approximately 38 cm, the six-letter strings subtended a horizontal visual angle of 2.25° and a vertical visual angle of .60°. The displays were presented in the upper center of the screen. The single-letter target was positioned to appear two lines above Serial Position 3 of the string display, a vertical visual angle separation of 1.65°. The RTs were measured from the time the video was turned on for the letter-string displays. A 1-kHz clock provided RT measurements accurate to milliseconds.

Results

An analysis of variance was carried out on the mean RTs for correct responses for the 11 subjects, with the four sessions, the two levels of positional frequency, orthographic regularity, and test type (target vs. catch trial) as factors. Table 1 presents the mean RTs for target and catch trials as a function of positional frequency and orthographic regularity. The RTs averaged 16 msec longer for low than for high positional frequency, $F(1, 10) = 16.64$, $p < .005$. Responses were 9 msec faster for orthographically regular than for orthographically

Table 1
Mean Reaction Times (in msec) for Target and Catch Trials in Experiment 1 as a Function of Positional Frequency (High or Low) and Orthographic Regularity

Orthographic regularity	Target		Catch	
	High	Low	High	Low
Regular	622	639	696	713
Error %	2.5	3.0	2.0	1.8
Irregular	631	639	706	729
Error %	2.5	4.0	1.8	2.0

irregular strings, $F(1, 10) = 6.91$, $p < .05$. Catch trials produced RTs that were 78 msec slower than RTs on target trials, $F(1, 10) = 15.95$, $p < .005$. The RTs decreased from 708 msec in Session 1 to 639 msec in Session 4, but this effect was not statistically significant, $F(3, 30) = 1.72$, $p > .10$. Also, sessions did not interact with any of the other variables. No other source of variance approached significance in the analysis.

A second analysis was carried out to evaluate whether the RTs on catch trials were sensitive to the similarity between the target letters and the letters in the catch string. The analysis was directed at finding out whether RT was a function of the number of letters in the catch string that were visually similar to the target letter. To do this, the letters of the alphabet were grouped into six sets based on the similarity results of Bouma (1971). These six sets are as follows: (m, n, r, u, v, w), (a, s, x, z), (c, e, o), (b, d, h, k), (f, i, j, l, t), and (g, p, q, y). The relationship between each target letter and catch string was defined in terms of the number of letters in the string that were members of the same set as the target letter. For example, the test string *lisver* would have two letters from the same set as the letter *t* and two from the same set as *m*. For each subject and for each of the six types of target letters, an RT was computed as a function of the number of letters in the catch string similar to the target letter. If any subject had fewer than four observations at a particular condition, this condition was eliminated from the analysis for all subjects. The analysis indicated that RT was a direct function of the number of letters in the catch string that were similar in shape to the target letter. With no similar letters in the test string the RT was 685 msec, whereas the RTs were 724, 736, and 755 msec for catch strings with one, two, and three similar letters, respectively. This effect of number of similar letters was highly significant, $F(3, 30) = 18.86$, $p < .001$.

A similar analysis was carried out on the mean RTs for target trials as a function of the number of letters in the test string similar to the target letter. In contrast to the catch trials, there was not a consistent increase in the RTs with increases in the number of letters of the test string similar to the target letter. The RTs for target strings that had one, two, three, and four letters similar to the target letter averaged 641, 624, 635, and 633 msec, respectively, $F(3, 30) < 1$. In contrast to the orderly increases on catch trials, there appears to be no systematic effect of letter class similarity on target trials.

Experiment 2

Method

Subjects. Sixteen sixth-grade students, 5 male and 11 female, participated in individual 1½-hr testing sessions. Two additional students' data were lost because of equipment failures. Chronological ages of the subjects ranged from age 11–0 to age 12–1. Reading comprehension was evaluated by administering the comprehension subtest of the Gates-MacGinitie Reading Test (1965, Survey D, Form 1). Comprehension grade level scores varied from 5.3 to 12+ with a mean grade level of 9.5. All subjects participated in response to advertisements in local newspapers and were paid $2 for their participation.

Stimuli and apparatus. The stimuli and apparatus were the same as for Experiment 1 with the exception that only List 1 was used.

Procedure. Each subject's session began with administration of the 25-min written comprehension test. After completing the reading test, the subject was seated before the computer terminal and the task explained. The remainder of the session was conducted in the same fashion as the first session of Test Day 1 in Experiment 1. Accordingly, each subject was tested for 50 yes–no trials, 50 practice trials, and 320 trials from List 1 in the experiment proper, giving roughly 80 observations per subject at each of the four experimental conditions (less error trials). As in Experiment 1, yes responses were given with the preferred hand.

Results

The mean correct RTs and their associated error percentages are presented in Table 2. Although the RTs were about 12 msec faster for regular than for irregular strings and about 12 msec faster for high than for low positional frequency, an analysis of variance revealed that neither result was significant. These results replicate those found with adult subjects, except that the small differences were statistically significant for the adults but not for the sixth-grade readers. The only statistically significant result was the 65-msec mean difference between target trials and the slower catch trials, $F(1, 15) = 16.11$, $p < .005$. However, this advantage in RTs on target trials appears to be at least partially due to higher error rates on those trials. Fourteen of the 16 subjects (significant by a sign test, $p < .02$) were more accurate in responding to catch trials than to target trials.

Analyses of similarity between catch string letters and target letters were made as in Experiment 1. The children's results exactly replicate the adult data. On catch trials, RTs average 876, 935, 977, and 1,080 msec for zero, one, two, and three similar letters, respectively, $F(3, 45) = 10.50$, $p < .001$. A similar analysis of the target trials revealed that RTs did not increase as a function of increasing numbers of letters of the same class as the target. Average RTs for target trials were 868, 840, 891, and 874 msec, for one, two, three, and four similar letters, respectively, $F(3, 45) = 1.77$, $p > .20$. These results contrast with those found for catch trials, and together the results provide an exact replication of the adult performance in Experiment 1.

To provide a direct comparison between the sixth-grade and adult readers, an analysis of variance was carried out on the results from both groups. For direct comparability, only Session 1 on the adult data was included and the five slowest sixth-graders were eliminated to provide an equal number of subjects in the two groups to be compared. The analysis indicated that both summed positional frequency and orthographic regularity were significant and that these effects did not interact with reader group. The RTs to irregular strings averaged 19 msec slower than RTs to regular strings, $F(1, 20) = 13.48$, $p < .005$; RTs to high positional frequency strings were 18 msec faster than RTs to low positional frequency strings, $F(1, 20) = 13.73$, $p < .005$. The RTs on target trials were 65 msec faster than on catch trials, $F(1, 20) = 29.49$, $p < .001$. Finally, the sixth-grade readers were 123 msec slower than the adult readers, $F(1, 20) = 6.90$, $p < .025$. This analysis shows complete agreement between the two groups of readers with respect to the variables manipulated in the experiments.

Table 2
Mean Reaction Times (in msec) for Target and Catch Trials in Experiment 2 as a Function of Positional Frequency (High or Low) and Orthographic Regularity

Orthographic regularity	Target High	Target Low	Catch High	Catch Low
Regular	850	848	907	934
Error %	8.4	7.0	4.8	3.6
Irregular	858	878	922	929
Error %	7.7	6.9	4.1	2.7

Discussion

Experiments 1 and 2 demonstrate that the target search task is relatively insensitive to the orthographic structure of the test letter strings. Only very small effects of orthographic structure were apparent, whereas target search times on catch trials were critically dependent on the number of letters in the test string similar to the target letter. In terms of our model, this means that the observer was usually capable of responding at the level of feature detection before recognition of the letters in the test string was complete.

One observation appears to be inconsistent with the idea of early responses on catch trials in the target search task. Across the two groups of readers, average RTs on catch trials were about 72 msec slower than average RTs on target trials. If subjects could terminate their search before all letters were recognized on some catch trials, then these RTs might be expected to be shorter than RTs on target trials. However, longer RTs on catch trials might result from a different stage of processing than that responsible for the similarity effect. The common results in a wide variety of tasks is that negative responses take longer than positive responses. Subjects may tend to hesitate or double check their decision on catch trials, adding to the overall RT. Some evidence for this possibility comes from the significantly higher error rates on target than on catch trials. A second reason for longer RTs on catch trials might be that all subjects responded "yes" with their preferred hand. Accordingly, absolute differences in RTs between target and catch trials are not valid indexes of a feature detection strategy in the target search task.

The feature detection strategy in target search appears to neutralize utilization of the orthographic structure of letter strings. According to our model, what is required to assess the use of orthographic structure is a task that requires primary recognition of the letters of the test string. Consider the task in which the test string is presented under restricted viewing conditions followed by presentation of the target letter. In this task, the subject still indicates whether or not the target letter was contained in the test string, but must resolve the letter string to the deepest level possible (Juola et al., 1974; Thompson & Massaro, 1973). Given that the display test must be processed through the stage of primary recognition, we should be able to assess the psychological validity of various descriptions of orthographic structure.

Experiment 3

Method

Subjects. Ten introductory psychology students, 5 male and 5 female, participated for 1 hr a day on 2 consecutive days and received extra point credit toward their psychology grades. The data from 3 additional subjects were lost, in two cases because of failure to perform the task as instructed and in the third case because of equipment malfunctions.

Apparatus and materials. The stimulus materials and apparatus were the same as in Experiment 2. Because the task was changed from a precued target search to a postcued target search, the experimental display sequence was reprogrammed as follows. A cardboard mask with a rectangular aperture was affixed to the face of the CRT screen. This window defined the area where the displays were presented and served as a fixation box. A trial began with the presentation of the six-letter stimulus string for a brief, controlled duration followed immediately by the masking stimulus, six uppercase *X*s. The masking stimulus was presented for 250 msec and followed by the target letter, which remained in view until the subject responded. The target letter was presented on the same line as the stimulus and mask strings but three character positions to the left of the initial letter position of the stimulus string.

The stimulus string exposure duration was individually determined for each subject during the practice trials. Because of the 60-Hz refresh rate for the CRT, 1 refresh cycle (16.7 msec) was chosen as the basic time unit. The number of cycles needed to achieve an overall accuracy level of 75% was determined on line by a modified version of the PEST algorithm (Taylor & Creelman, 1967). An adjustment of 1 or 2 cycles was made after each block of trials, if necessary, to maintain accuracy at 75%. Exposure times remained equivalent across conditions, since each block contained equal numbers of strings in each stimulus category. The mean exposure duration for the 10 subjects was 8.5 cycles or 142 msec. The range of average exposure durations across subjects varied between 2.1 and 14.8 cycles.

Procedure. The subjects were informed that the exposure duration would be brief and would be adjusted during the session to maintain an accuracy of 75%. It was emphasized that the most accurate judgments possible were desired on every trial. The subjects were also told that half the trials would be target trials and half would be catch trials.

To acquaint the subjects with the response procedure and visual display, each day's session began with 10 trials of responding to the words *yes* and *no*. On the first day the yes–no trials were followed by four 50-trial blocks of practice trials. For the practice trials the stimulus strings were six randomly selected letters. For these trials the initial exposure duration was set at 20 refresh cycles (333 msec) and adjusted, if necessary, every eighth trial. The practice trials were followed by four 80-trial experimental blocks. The procedure for the second day was similar except that only two 50-trial practice blocks were administered and the initial exposure duration for the day was set at the final exposure duration reached the preceding day. On both days the subjects were given short rest breaks between blocks of trials.

Results

The average percentages of correct responses on the target and catch trials at each of the four experimental conditions are presented in Table 3. Regular strings were recognized 4% more accurately than irregular strings, $F(1, 9) = 9.67$, $p < .025$. Strings high in positional frequency were recognized 5% more accurately than strings low in positional frequency, $F(1,9) = 38.61$, $p < .001$. The interaction of regularity and positional frequency was not significant, $F(1, 9) = 1$. No other sources of variance were significant.

Performance was analyzed as a function of the similarity of the target letters to the letters in the test items on catch trials. There was no significant effect of the number of similar letters in the catch strings. Performance averaged 84%, 81%, 82%, and 76% correct for zero, one, two, and three similar letters, respectively, $F(3, 27) = 1.97$, $p > .10$. A similar analysis showed no significant effects of similarity on target trials. Performance averaged 79%, 80%, 81%, and 86% correct for one, two, three, and four similar letters in the target string, $F(3, 27) = 2.64$, $p > .06$.

Discussion

In agreement with our hypothesis, the accuracy task with limited stimulus information and with the target letter presented after the test display appears to be more sensitive to the orthographic structure of the test strings. An orthographically regular string high in positional frequency was recognized 9% better than an irregular low positional frequency string. This result contrasts with the 22-msec difference in the RT task when the target letter was given before the test string. Although it might be argued that these results are not directly comparable, the difference in similarity effects in the two tasks supports the idea of a greater utilization of orthographic structure in the accuracy task. In contrast to the catch strings

Table 3
Average Percentage of Correct Responses for Target and Catch Trials in Experiment 3 as a Function of Positional Frequency (High or Low) and Orthographic Regularity

Orthographic regularity	Target		Catch	
	High	Low	High	Low
Regular	86.0	78.9	85.5	81.5
Irregular	80.2	75.2	83.0	78.2

Note. Each cell is based on 80 observations for each of 10 subjects.

in the RT task, no consistent effect was observed in the accuracy task. The critical variable determining large effects of similarity is the degree to which the subject terminates processing before recognition is complete. If the subject is given the target before the test string and speed of response is stressed, large effects of similarity should be observed. If presentation of the target is delayed until after the test string has been resolved, similarity should not have much effect. According to this analysis, tasks that eliminate effects of similarity are more likely to show positive effects of orthographic structure.

The orthographic structure effects also provide some evidence against the positional uncertainty hypothesis of Estes (1975). In his view, orthographic structure does not facilitate resolution of the letters in a string but simply reduces uncertainty about their relative spatial positions. In our experiment, identification of the letters was critical to performance whereas their spatial position was irrelevant to the task. Accordingly, if subjects identified the letters equally for both the regular and irregular strings, as Estes would predict, no differences should have been observed.

The small effects in the RT task might be claimed to be due to a poor selection of test items in the present experiments. It might be argued, for example, that the regular items are not all that regular and, therefore, the regular strings do not differ very much from the irregular strings. Although the positive results in the accuracy task argue against this interpretation, it seemed worthwhile to provide an independent assessment of the regularity of the test strings. To provide this assessment, college students were asked to rate each string in terms of how much it looked like a real English word. These ratings also provide a converging measure of the degree to which orthographic regularity and summed positional frequency are psychologically real descriptions of the reader's knowledge of orthographic structure.

Experiment 4

Method

Subjects. Fifty-eight college students were recruited as in the previous experiments. One subject was eliminated from the analysis because he used the scale backwards.

Stimulus lists. The 320 strings of Lists 1 and 2 were randomized and typed, 40 items per page. The order of the items on each page was constant across subjects, although each subject received a different random order of the eight pages. Each word was typed in lowercase letters with an underlined blank area next to it.

Procedure. Subjects were tested in groups of 8 to 10. The subjects were told the general nature of the experiment and the rating scale to be used. The scale was graphically represented on the blackboard for reference purposes as a line with 10 even graduations. All subjects completed the ratings in 30 to 45 min. They were instructed to rate each letter string on a scale of 1 to 10 according to how much it looked like a real English word. Strings that were extremely close were to be given high ratings, while strings that were not very close were to be given low ratings. Subjects were encouraged to skim over the strings before they began in order to obtain an idea of their range of variation. It was emphasized that the full scale was to be used. The "best" items were to be given a rating of 10 and the "worst" a rating of 1.

Table 4
Average Ratings in Experiment 4 as a Function of Summed Positional Frequency and Orthographic Regularity

Positional frequency	Regularity: Regular	Regularity: Irregular	*M*
High	6.82	3.30	5.06
Low	5.20	2.91	4.05
M	6.01	3.11	

Results

Both positional frequency and orthographic regularity had a significant effect on the ratings. Regular strings received an average rating of 6.06, which was twice the average rating of 3.02 of the irregular strings, $F(1, 56) = 337$, $p < .001$. Strings high in positional frequency were rated as more like English words than strings low in positional frequency (5.06 vs. 4.02), $F(1, 56) = 338$, $p < .001$; but the effect of positional frequency was almost entirely due to the regular strings, $F(1, 56) = 249$, $p < .001$. Table 4 shows the interaction of positional frequency and regularity.

Discussion

The ratings of the test strings revealed that subjects could easily discriminate items high in orthographic structure from those low in orthographic structure. Rule-governed regularity was about three times as effective in discriminating the test strings than was summed positional frequency. However, either summed positional frequency did influence the subjects' rating responses or, contrary to our rule-governed assignment, the regular strings were not equally regular for the high and low positional frequencies. If the latter was the case, some or all of the advantage enjoyed by the high positional frequency strings could have been due to regularity.

General Discussion

The present research addressed the question of whether or not the target search latencies are very sensitive to the orthographic structure of the test letter strings. Only a small, but sometimes significant, effect of orthographic structure was observed. On the other hand, target search times for catch trials were critically dependent on the number of letters in the test word that belonged to the same letter class as the target letter. The RTs on catch trials were slower to the degree that the catch strings contained letters of the same class as the target. In terms of our stage model, this means that the observer was sometimes capable of responding at the level of feature detection before recognition of the letters in the test string was complete.

If we assume that (a) a sequence of letters can be processed in parallel, (b) features of individual letters are extracted continuously, (c) feature extraction processes operate on all letter positions independently and with unlimited capacity, and (d) comparisons between extracted features in the target letter can occur before perception is complete, then a relatively parsimonious description of the results can be given. Backward masking and partial report experiments (Averbach & Coriell, 1961; Massaro, 1975a; Sperling, 1960) have shown that the resolution of the visual display occurs gradually over time. Massaro and Klitzke (1977) have previously conceptualized the perception of letters as occurring in a two-stage process. The overall shape of each letter is assumed to be resolved in the first stage; the details of the letter are resolved in the second stage. The reader does not have to complete both stages of processing for each letter, but can in many cases identify the letters unambiguously after the first stage of processing. In target search tasks, the subject can select a response after either stage, depending on the confidence the subject has in the decision at the end of the first stage. The subject maintains a fixed criterion to keep the false alarm rate minimal. If the information available to the subject at the end of the first stage is sufficient to respond correctly with probability P_c, and $1-P_c < P_f$ where P_f is the maximum false alarm rate the subject will tolerate, then the subject outputs the response. Otherwise the second stage of processing is completed. This model can be extended to account for the results of the present experiments. It is assumed that letter features are continuously extracted in parallel across all of the letters in the test string. A subject can initiate a response at any point in this processing sequence. If the subject is given the target letter before the test display presentation, each letter in the string does not have to be completely processed. On catch trials, the subject does not have to recognize all of the letters in the test string, but only has to process enough of each letter to insure that it is not the same as the target letter. On target trials, enough features from the appropriate letter must be extracted in order to identify it unambiguously.

The processing time for each letter in the test string on catch trials will be a direct function of the number of features it shares with the target. To the extent the letter does not share features with the target, it can quickly be rejected. Accordingly, test strings that contain nothing but highly dissimilar letters from the target should be responded to very quickly, whereas RTs should be large for test strings with a large number of items similar to the target letter. In contrast to catch trials, no effects of letter similarity should be observed on target trials. Regardless of the similarity of the nontarget letters in the test string, the target letter must still be resolved sufficiently in order to execute a positive response. Since it is assumed that processing occurs in parallel, only the time to identify the target letter is critical on positive target trials.

The support for this model of letter recognition comes from the similarity analysis carried out in Experiments 1 and 2. We assume that letters of the same letter class share more features than those not of the same class. Accordingly, RTs on catch trials should increase with increases in the number of letters of the same class as the target letter. In agreement with this prediction, average RTs increased steadily as the number of letters of the same class increased from zero to three. Further support for the model comes from the negative findings on positive target trials. RTs showed no consistent changes as the number of letters of the same class as the target was increased from one to four.

Other models of the target search task have been proposed, most notably Gardner's (1973) independent channels confusion model and Estes' (1972) interactive channels model. Both of these models assume that features are extracted in parallel from all letter positions in a visual display. Gardner's model assumes that feature extraction processes are independent at all letter positions for displays in foveal vision, but that post-perceptual decision processes permit confusions between the target letter and confusable noise elements in the display. Although this model could be modified to predict the increase in RT on catch trials with more numerous noise letters similar to the target letter, Gardner assumes that decision processing begins only after perceptual recognition is complete and that decision latency is unaffected by the extent of confusability between target and noise elements. Therefore, the current version of Gardner's model predicts no effect of target letter similarity on RTs to target or catch trials.

Estes' (1972) model assumes that target and nontarget (noise) letters compete for feature extraction resources. Thus, the greater the similarity between target and noise letters, the greater the competition. If a target letter is accurately detected, a primary detection response is evoked and processing stops which results in a rapid yes response. If no primary detection process occurs, then processing continues and secondary decision processes must select a yes or no response. This model correctly predicts that catch trial RTs would increase with increasingly similar noise letters because of the competition during feature extraction. Without further assumptions, however, this model would incorrectly predict that RT to target trials would also be an increasing function of similarity between the target letter and the noise letters in the display, although the magnitude of this effect need not be as great as on catch trials. Thus, neither Gardner's nor Estes' model adequately predicts the results of Experiments 1 and 2 without additional assumptions.

It is necessary to assume that the feature detection strategy that we have proposed is inconsistent with the active utilization of orthographic structure in the target search task. Only small effects of orthographic regularity will be found in this task to the extent that subjects actively utilize the feature detection strategy. We predicted, however, that the utilization of orthographic structure would occur when the readers were required to resolve all of the letters in the test string to the deepest level possible. If the subjects are no longer able to reject a partially resolved letter as they can in the target search task, then it is to their advantage to utilize what they know about the structure of letter strings in order to identify all of the letters that make it up. We encouraged the readers in Experiment 3 to operate along these lines by presenting the test string first, followed by a single target letter. Since the subjects did not know the target letter in advance, they had to resolve all of the letters in the test string in order to perform the task correctly.

Similar trade-offs between the feature detection strategy and the utilization of orthographic structure have been reported in other studies. Johnston and McClelland (1974) demonstrated the importance of processing strategy on the perception of word strings. Subjects either were told to attempt to see a whole word or were told the critical letter position in a Reicher-Wheeler task (see Reicher, 1969; Wheeler, 1970). Subjects were about 7% more accurate with the whole-word than with the single-letter processing strategy. In terms of our model, subjects utilized the orthographic structure available in the word in the whole-word processing strategy but did not take advantage of the letter context when attention was directed to the critical spatial position.

In a study by Appelman (1976), subjects were presented two words or two nonwords in a same–different task. Subjects were 8% more accurate on word than on nonword trials. In a second experiment, only a single test string was presented with a target letter above or below the critical letter in the test string. Subjects indicated whether the target letter was the same as or different from the critical letter in the test string. The word advantage was eliminated in this task. In terms of our model, subjects processed the letter strings through primary recognition in the first case but not in the second. In the second case, the target letter would encourage subjects to process only the critical letter in the test string. Therefore, orthographic structure would not be utilized and no word advantage would be observed.

We have interpreted the processing advantages with highly structured strings in terms of a facilitation of letter recognition. An alternative hypothesis would claim that highly structured strings allow the direct recognition of higher-order units such as spelling patterns or words, which would result in more efficient processing of these strings. The higher-order unit model, however, does not necessarily predict that a target letter will be found more quickly in a structured string than in an unstructured string. In fact, recent higher-order unit models have been developed to make just the opposite prediction: it should take longer to find a target letter in a word than in a nonword string (Johnson, 1975). Extending this class of models to the current RT task would predict a disadvantage of the regular test strings; but the opposite results were observed. Until the letter and higher-order unit models can be differentiated, we prefer to interpret the results in terms of the facilitative effect of orthographic structure on letter recognition.

In summary, our results and analyses of the target search task lead to the conclusion that the target search RT task is relatively insensitive to the presence of orthographic structure in the letter strings to be searched. The task promotes utilization of a feature detection strategy, which appears to be inconsistent with the active utilization of orthographic structure in processing letter strings. However, despite this insensitivity, an effect of orthographic structure was found for both target search RT and accuracy tasks. These effects could not be attributed solely to the effects of either a rule-governed or a single-letter positional frequency description of orthographic structure. Either both these descriptions have psychological reality, or some as yet unexplicated description that encompasses the descriptive power of both measures is necessary to understand the effects of orthographic structure on the visual processing of letter strings.

References

Aderman, D., & Smith, E. E. Expectancy as a determinant of functional units in perceptual recognition. *Cognitive Psychology*, 1971, *2*, 117–129.

Appelman, I. B. The word-superiority effect: Dependence on short-term memory factors. *Memory & Cognition*, 1976, *4*, 156–161.

Averbach, E., & Coriell, A. S. Short-term memory in vision. *Bell System Technical Journal*, 1961, *40*, 309–328.

Baron, J., & Thurston, I. An analysis of the word-superiority effect. *Cognitive Psychology*, 1973, *4*, 207–228.

Bouma, H. Visual recognition of isolated lower-case letters. *Vision Research*, 1971, *11*, 459–474.

Estes, W. K. Interactions of signal and background variables in visual processing. *Perception & Psychophysics*, 1972, *12*, 278–285.

Estes, W. K. The locus of inferential and perceptual processes in letter identification. *Journal of Experimental Psychology: General*, 1975, *104*, 122–145.

Gardner, G. T. Evidence for independent parallel channels in tachistoscopic perception. *Cognitive Psychology*, 1973, *4*, 130–155.

Gates-MacGinitie reading test. New York: Teachers College Press, 1965.

Gibson, E. J., & Levin, H. *The psychology of reading*. Cambridge, Mass.: MIT Press, 1975.

Gibson, E. J., Tenney, Y. J., Barron, R. W., & Zaslow, M. The effect of orthographic structure on letter search. *Perception & Psychophysics*, 1972, *11*, 183–186.

Gilford, R. M., & Juola, J. F. Familiarity effects on memory search and visual search. *Bulletin of the Psychonomic Society*, 1976, *7*, 142–144.

Herrmann, D. J., & McLaughlin, J. P. Language habits and detection in very short-term memory. *Perception & Psychophysics*, 1973, *14*, 483–486.

Huey, E. B. *The psychology and pedagogy of reading*. Cambridge, Mass.: MIT Press, 1968. (Originally published, 1908.)

James, C. T., & Smith, D. E. Sequential dependencies in letter search. *Journal of Experimental Psychology*, 1970, *85*, 56–60.

Johnson, N. F. On the function of letters in word identification: Some data and a preliminary model. *Journal of Verbal Learning and Verbal Behavior*, 1975, *14*, 17–29.

Johnston, J. C., & McClelland, J. L. Visual factors in word perception. *Perception & Psychophysics*, 1973, *14*, 365–370.

Johnston, J. C., & McClelland, J. L. Perception of letters in words: Seek not and ye shall find. *Science*, 1974, *184*, 1192–1194.

Juola, J. F., Leavitt, D. D., & Choe, C. S. Letter identification in word, nonword, and single-letter displays. *Bulletin of the Psychonomic Society*, 1974, *4*, 278–280.

Krueger, L. E. Search time in a redundant visual display. *Journal of Experimental Psychology*, 1970, *83*, 391–399. (a)

Krueger, L. E. Visual comparison in a redundant display. *Cognitive Psychology*, 1970, *1*, 341–357. (b)

Krueger, L. E. Familiarity effects in visual information processing. *Psychological Bulletin*, 1975, *82*, 949–974.

Krueger, L. E., Keen, R. H., & Rublevich, B. Letter search through words and nonwords by adults and fourth-grade children. *Journal of Experimental Psychology*, 1974, *102*, 845–849.

Krueger, L. E., & Weiss, M. E. Letter search through words and nonwords: The effect of fixed, absent, or mutilated targets. *Memory & Cognition*, 1976, *4*, 200–206.

Kucera, H., & Francis, W. N. *Computational analysis of present-day American English*. Providence, R.I.: Brown University Press, 1967.

Manelis, L. The effect of meaningfulness in tachistoscopic word perception. *Perception & Psychophysics*, 1974, *16*, 182–192.

Mason, M. Reading ability and letter search time: Effects of orthographic structure defined by single-letter positional frequency. *Journal of Experimental Psychology: General*, 1975, *104*, 146–166.

Massaro, D. W. *Experimental psychology and information processing*. Chicago: Rand-McNally, 1975. (a)

Massaro, D. W. Primary and secondary recognition in reading. In D. W. Massaro (Ed.), *Understanding language: An information processing analysis of speech perception, reading, and psycholinguistics*. New York: Academic Press, 1975. (b)

Massaro, D. W. (Ed.) *Understanding language: An information processing analysis of speech perception, reading, and psycholinguistics*. New York: Academic Press, 1975. (c)

Massaro, D. W., & Klitzke, D. Letters are functional in word recognition. *Memory & Cognition*, 1977, *5*, 292–298.

Massaro, D. W., & Schmuller, J. Visual features, preperceptual storage, and processing time in reading. In D. W. Massaro (Ed.), *Understanding language: An information processing analysis of speech perception, reading, and psycholinguistics*. New York: Academic Press, 1975.

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

Miller, G. A., Bruner, J. S., & Postman, L. Familiarity of letter sequences and tachistoscopic identification. *Journal of General Psychology*, 1954, *50*, 129–139.

Neisser, U. Visual search. *Scientific American*, 1964, *210*, 94–102.

Reicher, G. M. Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology*, 1969, *81*, 275–280.

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

Sperling, G. The information available in brief visual presentations. *Psychological Monographs*, 1960, *74*(11, Whole No. 498).

Taylor, M. M., & Creelman, C. D. PEST: Efficient estimates on probability functions. *Journal of the Acoustical Society of America*, 1967, *41*, 782–787.

Thompson, M. C., & Massaro, D. W. Visual information and redundancy in reading. *Journal of Experimental Psychology*, 1973, *98*, 49–54.

Venezky, R. L., & Massaro, D. W. The role of orthographic regularity in word recognition. In L. Resnick & P. Weaver (Eds.), *Theory and practice of early reading*. Hillsdale, N. J.: Erlbaum, in press.

Wheeler, D. D. Processes in word recognition. *Cognitive Psychology*, 1970, *1*, 59–85.

Woodworth, R. S. *Experimental psychology*. New York: Holt, Rinehart & Winston, 1938.

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(*Appendixes follow*)

Appendix A

Selection of Orthographically Regular and Irregular Strings

From the list of permutations of a real word for a particular summed positional frequency class (high or low), a string was selected for the orthographically irregular list if it contained any of the following spellings:

1. An unpronounceable initial or final cluster (e.g., *tproer, aorlld*)
2. A pronounceable, but orthographically illegal, spelling for an initial or final consonant or consonant cluster (e.g., *cc*apet, ae*rrgd*)
3. An illegal vowel spelling (e.g., gr*eee*d, fr*uu*et)
4. An unpronounceable medial cluster (e.g., *efcf*oi, e*ttrb*e).

Rules for pronounceability and orthographic legality were derived by extending the rules given in Venezky and Massaro (in press). These in turn are based on the letter–sound patterns found in approximately 20,000 English word types. When these criteria failed to yield an illegal string, implausible spellings were selected. These usually included marginally pronounceable medial consonants that would occur only in compound words (e.g., e*rptr*o), or a rare vowel spelling (e.g., *y*lelra).

Regular strings were selected (a) to be pronounceable, (b) to contain common vowel and consonant spellings, and (c) to have not more than three letters for a medial consonant cluster, if one occurred. No control was placed on number of syllables, however. When these criteria failed to yield a regular string, the rules were relaxed to allow uncommon doubled consonants (e.g., cota*nn*) and uncommon final vowels (e.g., inalm*a*, tress*i*).

Appendix B

Table B1
The Words, the Four Permutations Used in the Experiments, and the Summed Positional Frequency f *of Each for List 1 (First 40 Words) and List 2 (Last 40 Words)*

Words	*f*	High-Regular	*f*	High-Irregular	*f*	Low-Regular	*f*	Low-Irregular	*f*
modern	1010	remond	1600	rmnoed	1651	endrom	426	rdenmo	431
minute	1167	muinet	1446	mntieu	1406	itenum	383	inemtu	384
itself	751	siflet	1664	tlfies	1674	estfil	429	eflsti	428
master	1727	matser	1671	mrates	1693	estram	465	emtrsa	471
island	1000	sinald	1505	lanisd	1490	indsal	372	inlsda	372
happen	1420	phanep	1325	pahpne	1271	enpaph	375	ehpnpa	393
ground	1264	gonurd	1278	ruognd	1266	odgrun	342	ondrgu	346
golden	1417	genold	1530	olnged	1539	engdol	458	eldngo	459
garden	1568	nagred	1708	arnged	1721	edgran	416	ednrga	402
friend	1324	firden	1546	irfned	1560	endrif	372	efnrdi	371
finger	1530	firgen	1544	frnieg	1587	efgrin	428	inerfg	442
farmer	1719	ramfer	1573	afmrer	1372	ermraf	538	erarfm	533
during	1164	rigund	1293	uirgnd	1284	idgrun	328	undrgi	324
double	1171	boudel	1448	lbuoed	1599	odelub	286	ebdluo	271
direct	1073	tecird	1609	tericd	1615	edtric	447	etrcdi	447
broken	1467	ronkeb	1372	beoknr	1364	enbrok	391	erknbo	392
belong	1356	golben	1377	benolg	1378	englob	415	onelgb	414
behind	1657	hibned	1655	hnbied	1654	endhib	332	inedhb	325
around	1411	naroud	1313	uoarnd	1304	oduran	441	ndorau	441
amount	1048	manout	1054	uaotnm	1061	otunam	440	nmutao	440
almost	955	samolt	1480	maotls	1479	otslam	454	osltma	447
action	988	acoint	1223	coaitn	1223	incato	455	ntiaco	445
yellow	825	lewoly	1278	olwley	1215	elylow	470	eylwol	455
wonder	1526	wroned	1719	wnroed	1737	edwron	457	edwnro	444
winter	1584	werint	1513	wtnier	1525	etwrin	476	etwnri	503

(*table continued*)

Table B1 (*continued*)

Words	f	High-Regular	f	High-Irregular	f	Low-Regular	f	Low-Irregular	f
travel	1321	vartle	1466	avrlet	1475	trelva	528	tlerav	516
toward	1205	watord	1447	waotrd	1458	otdraw	359	rtdwao	378
stream	918	tasmer	1608	mrtaes	1603	estram	465	mtersa	496
spread	1287	sardep	1687	prsaed	1692	edrsap	417	esrdpa	429
single	1413	nigles	1491	sgniel	1528	engsil	398	ngelsi	379
simple	1411	limpes	1643	pmlies	1649	empsil	342	esplmi	282
silver	1657	lisver	1492	serilv	1538	evsril	430	rseliv	444
second	1725	socend	1621	cdnoes	1559	endsoc	395	escndo	389
remain	1013	naimer	1528	aeminr	1526	ineram	390	rmenai	461
result	1357	surtel	1651	lrtues	1689	estrul	464	elsrtu	519
reason	1081	sarone	1712	sraoen	1677	oseran	458	esnroa	445
prince	1008	cipner	1531	pcnier	1583	encrip	426	enrcpi	417
period	1679	podier	1735	peoird	1714	edirop	413	erdpio	433
number	1310	murben	1390	bnruem	1407	embrun	364	rnembu	385
bridge	1001	ribged	1660	berigd	1678	egdrib	285	igerdb	270
accept	810	paccet	1580	ccapet	1438	ectcap	408	ctecpa	396
spirit	818	pirist	1256	pitisr	1208	isprit	475	tpsrii	455
report	1214	troper	1508	tproer	1531	trerop	605	erptro	658
really	1348	leraly	1390	lrlaey	1457	lyeral	506	ylelra	521
office	902	cofife	1244	fcfieo	1299	eficof	365	efcfoi	332
return	1247	rutner	1538	tnruer	1546	ertrun	657	rrentu	649
refuse	1293	sufeer	1662	srfuee	1782	eseruf	312	esrefu	548
regard	1342	drager	1439	aerrgd	1468	edgrar	497	rdgera	607
season	1227	asones	1577	seoans	1597	esosan	564	nsseoa	546
school	772	soloch	1067	hcools	1137	oschol	442	lsocho	437
sister	1780	sirset	1772	srties	1967	tressi	560	esrtsi	620
street	1754	rettes	1986	srttee	1917	eterts	771	rteste	882
sudden	1409	desund	1498	dsnued	1568	esddun	371	dnesdu	373
summer	1555	merums	1303	srmmeu	1355	emsrum	339	rsemmu	357
valley	1541	valely	1215	llvaey	1322	vyelal	398	ylelav	399
across	1093	casors	1359	saocrs	1374	osscar	492	ocssra	485
afraid	1067	afriad	1265	araifd	1282	idaraf	414	rdfaai	418
affair	690	faraif	922	afaifr	927	ariffa	480	rfaafi	470
animal	590	lamian	1148	aaimln	1144	inalma	452	ilnmaa	427
appear	769	papare	1225	aappre	1238	eparap	457	pperaa	453
arrive	1275	vairer	1516	rraiev	1504	evirar	567	rreaiv	569
battle	1592	tabtel	1518	beatlt	1502	ettlab	522	etlatb	516
became	1244	ceabem	1574	bcmaee	1572	ebecam	291	ebeamc	332
become	1335	boceem	1560	mbcoee	1534	ebecom	338	emeobc	396
before	1458	boreef	1676	brfoee	1713	ebefor	516	oreefb	519
beside	1456	bidees	1732	bsieed	1701	edesib	316	iseedb	409
better	1931	betret	1830	brttee	1818	erbett	812	ettrbe	810
cannot	1148	cotann	1166	aoctnn	1192	ontcan	536	ncntao	534
chance	1072	cachen	1569	ccahen	1340	echcan	385	enhcca	280
decide	1344	cieded	1756	cdeied	1743	ededic	342	edeedc	415
degree	1730	gedeer	1663	greeed	1665	eredge	855	eeerdg	865
demand	1451	namded	1794	anmded	1639	eddman	393	ednadm	393
desire	1495	reised	1912	srdiee	1881	edesir	530	iseedr	623
dollar	929	lorald	1513	aorlld	1564	oldral	449	ollrda	449
effort	778	fofret	1543	ffroet	1523	etorff	464	efrfto	464
either	1500	heiter	1752	htriee	1789	hteeri	666	eherit	666
escape	696	caseep	1596	spcaee	1627	ecesap	364	aseepc	555
fellow	959	wollef	1363	llfoew	1283	ellfow	476	lwefol	461
future	1192	rufuet	1466	fruuet	1472	uferut	472	ertfuu	438
heaven	1597	haveen	1555	vhanee	1554	evehan	441	eneavh	429