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Visual, Orthographic, Phonological, and Lexical Influences in Reading

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The fuzzy logical model of perception (FLMP), used as a framework to analyze phenomena in reading, asserts that there are multiple influences on reading performance. Experiments on the dynamic interaction of letter information and orthographic context are presented. Previous results have supported the FLMP over a variety of interactive activation models. These findings indicated that lateral masking and the time course of processing must be accounted for in the theoretical prediction of letter and word recognition. A new finding is that the word superiority effect is not influenced by the nature of the backward masking stimulus, nor is it diminished with letter and word masks, contrary to the predictions of several extant explanations. The FLMP is extended to account for reaction time in reading. Perceptual recognition, naming, and lexical decision tasks reflect the influence of multiple sources of information. These include orthographic structure, spelling-to-speech correspondences, and word frequency. Reading can be productively analyzed as a prototypical pattern recognition situation in which the reader exploits multiple sources of information in perception and action.

In the early heady days of the cognitive revolution, it was natural to think in terms of strong opposing alternatives. In reading research, for example, the contrasting issues seemed to be clearly defined. Were words read as integral wholes, or did the recognition of letters mediate word recognition? Were words recognized directly from their visual configuration, or did a speech code (phonology) somehow mediate word recognition? Did lexical access involve just a single route from the visual input, or were there dual routes? These questions have continued to receive a good deal of attention during the last two decades of research.

Although these questions did not have simple answers, these binary contrasts were helpful in leading to the answers available to us today. We think it is fair to say that we understand the phenomena of interest surprisingly well—given the relatively short time since these questions were formulated. (Some binary contrasts still exist, however, such as the need for word-specific representations in naming and lexical decision tasks; Besner, Twilley, McCann, & Seergobin, 1990; Seidenberg & McClelland, 1989.) There is an impressive consensus on the processes involved in the early stages of reading written language. Although each researcher has taken a slightly different tack in the theoretical description, there is enough overlap to warrant optimism. Our summary of the state of the art in reading is no different; it is grounded in a general framework for pattern recognition that we have developed over the last several decades. The central assumption of this approach is that reading letters and words is fundamentally a pattern recognition problem. We begin with a description of the general model and its description of reading.

Fuzzy Logical Model of Perception (FLMP)

Within the framework of the FLMP, well-learned patterns are recognized in accordance with a general algorithm, regardless of the modality or particular nature of the patterns (Massaro, 1987; Oden, 1979). The model consists of three stages, as shown in Figure 1: feature evaluation, feature integration, and decision. These stages are illustrated to show their necessarily successive, but overlapping, processing over time. Written text is transduced by the visual system and makes available a set of primitive characteristics, called sensory cues or features. These features are evaluated to determine the degree to which each feature supports each potential alternative. In contrast to most models, the features are assumed to provide continuous rather than discrete information about each alternative. In this case, a particular feature supports a particular alternative to some continuous degree. The integration process combines the information from each feature to give an overall degree of support for each alternative. Finally, the decision process makes some judgment on the basis of the relative support for the relevant alternatives. (The reader is referred to the following articles for a more complete description of the framework and model: Cohen & Massaro, 1992; Massaro, 1987; Massaro & Cohen, 1991, 1993; Massaro & Friedman, 1990; Oden & Massaro, 1978.)

Given the recent popularity of chaos and nonlinear dynamics in the physical sciences, social scientists have become increasingly dissatisfied with linear models

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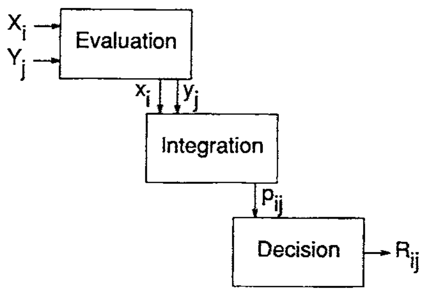

Figure 1. Schematic representation of the three stages involved in perceptual recognition. The three stages are shown to proceed left to right in time to illustrate their necessarily successive but overlapping processing. The sources of information are represented by uppercase letters X_i and Y_j. The evaluation process transforms these sources of information into psychological values (indicated by lowercase letters x_i and y_j). These sources are then integrated to give an overall degree of support for a given alternative p_{ij}. The decision operation maps this value into some response, R_{ij}, such as a discrete decision or a rating.

(Bechtel & Richardson, 1993; Van Orden & Goldinger, 1994). Although we take an information processing approach (Massaro & Cowan, 1993), we do not adhere to a linear model or necessarily to a linear systems analysis. The FLMP is, in fact, a nonlinear model. Independence at feature evaluation does not mean that the FLMP is necessarily linear or that we advocate a linear systems analysis. We remind the reader of our history of falsifying various linear (additive, averaging, single channel, and categorical) models (Massaro, 1987; Massaro & Cohen, 1990). It is important not to confuse the FLMP, nonlinearity and interactive activation. Both models are nonlinear, but they differ in their assumptions. The important difference seems to be the use of interactive activation, and this is why we have tested this assumption (Massaro & Cohen, 1991).

Processing Written Language

Reading involves much more than letter recognition. It also involves mapping strings of letters into words and meanings. It has been demonstrated that multiple sources of information contribute to letter recognition (Massaro & Hary, 1986; Oden, 1979). These sources of information have usually been characterized as various visual features that distinguish among the letters. Not surprisingly, multiple sources of information also contribute to word recognition. In addition to the visual information about the letters of the word, there is information about spelling (orthographic structure; Massaro, 1975b) and spelling-to-speech correspondences (phonology; Venezky & Massaro, 1987), and lexical identity. The extent to which a source of information contributes to performance depends on its information value; in general, the least ambiguous source will have the largest influence on performance (Massaro, 1987, chapter 7). For skilled readers and familiar words, the extraction of visual letter information and lexical access may be so quick that other nonvisual sources of information do not reveal much of an influence. However, with less familiar words or with beginning readers, nonvisual sources of information become increasingly important. For example, phonological information resulting from the encoding of letter-to-speech correspondences may be useful for beginning readers and may even influence skilled readers' processing of infrequent words and nonwords.

Stimulus (bottom-up) information about letters serves as the primary source of information used in reading. Another (top-down) influence is nonvisual information possessed by the sophisticated language user. One can distinguish five sources of nonvisual information that can aid the reader in decoding the written message. These sources are the orthographic, phonological, syntactic, semantic, and pragmatic structures that exist in English prose. The orthographic source constrains the observed spelling patterns in English. We know that words are separated by blank spaces and must have at least one vowel. Another source of sublexical information concerns the somewhat regular mapping between spelling and spoken language (at various times referred to as speech, phonology, or sound). We refer to information about spoken language as phonological without any commitment to a particular linguistic theory of representation. In English, letters and letter sequences tend to be associated with particular pronunciations. English spelling-to-sound is not perfectly regular in that a letter or a grapheme can usually be pronounced in several ways, as in the well-known hypothetical spelling *ghoti* for *fish* (*gh* as in *rough*, *o* as in *women*, and *ti* as in *nation*). Because of its dependence on deeper layers of language such as morphology and its relative inconsistency between spelling and sound, English is called a "deep" orthography. "Shallow" orthographies of languages have less dependence on deeper layers of language and a higher consistency between spelling and sound (Liberman, Liberman, Mattingly, & Shankweiler, 1980).

Today, almost all reading researchers in this area acknowledge several sources of information that contribute to the processing of written words. However, most models have the assumption that performance is influenced by only a single source at any given time. The best-known model is the dual-route model that allows both lexical and sublexical influences of print (Besner & Smith, 1992; Coltheart, Curtis, Atkins, & Haller, 1993). At the lexical level, the print can activate some semantic representation which, in turn, activates some phonological representation. The print can also activate a phonological word representation directly. In addition to these lexical influences (called an addressed route), it is assumed that the print can activate some speechlike code through the use of spelling-to-sound correspondence rules (called an assembled route). As now realized by several investigators, however, the sublexical activation of some speech code by print does not require rules; a simple associative process is all that is necessary. Venezky and Massaro (1987) formalized the associative nature of this process by quantifying the relationship between print and speech as a function of the regularity or relative frequency of their joint occurrence. Paap, Noel, and Johansen (1992) proposed a dual-route theory without rules and were able to modulate the relative contribution of one of these routes relative to the other. In the FLMP framework, the direct lexical and indirect spelling-to-sound routes are seen as having independent sources of information contributing to word recognition. The critical assumption of the FLMP is that the several sources of information simultaneously contribute to performance. In contrast to the dual-route model (in which only a single source is influential at any one time), the two sources of information are integrated to give an overall goodness-of-match to the possible word candidates. A formalization of the predictions of the FLMP is presented in the section titled Multiple Influences in Reading Tasks.

We take independence as the most parsimonious assumption about the multiple sources of information. As an example, orthographic constraints do not modify spelling-to-speech constraints; rather, both of these feed forward to constrain the recognition or memory of the word. This assumption of independence contrasts with the assumption of interactive activation in which the representation of one source of information is eventually modified by another. We have falsified the interactive activation account of the word superiority effect (WSE) in word recognition (Massaro & Cohen, 1991; Massaro & Sanocki, 1993).

Syntactic constraints establish the permissible occurrences of different parts of speech. For example, "The boy down fell the hill" is grammatically incorrect, perhaps making it more difficult to read the word *fell.* Semantic constraints allow the reader to predict the word or words that make the most sense in a given sentence context. "The hill fell down the boy" is syntactically correct but semantically anomalous. Pragmatic constraints exploit the intentional goals of the participants to achieve good communication. All of these sources of information allow us to agree on the meaning of the misspelled word in "Please clean the dirt from your shooz before walking inside."

Our first empirical study addresses the use of visual information and orthographic constraints in letter recognition. In terms of the FLMP, the visual stimulus is transformed by the visual system, and letter features are evaluated. Recognition, or the interpretation of this information, depends on the integration of these features with the information possessed by the reader about the occurrences of spelling patterns in English. This knowledge is sometimes referred to as orthographic redundancy; it reduces the number of valid alternatives a particular visual configuration can possess. Knowledge of English spelling enables the reader to extract meaning from a page of text without analyzing all the visual information that is present, or to identify words even when some of the visual information is incomplete or fuzzy. Research over the last century has shown that spelling constraints can facilitate the recognition of letter strings. Spelling constraints correspond to both lexical and sublexical information about letter identity. Reicher's (1969) controls for postperceptual guessing and forgetting revived interest in this phenomenon. He found that a letter was more accurately identified when presented in a word than when presented alone or in a nonword. This finding is called a WSE. Recent research analyzing the dynamic processing of letter information and spelling constraints has permitted additional tests of contemporary models of reading. We review this research and present a new experiment within this paradigm to further the assessment of these extant models.

Dynamic Interaction of Letter Information and Orthographic Context

Orthographic structure refers to the fact that a written language, such as English, follows certain rules of spelling (Venezky & Massaro, 1979). These regularities (which are based on both phonological and scribal constraints) prohibit certain letter combinations and make some letters and combinations much more likely in certain positions of words than others. Given that humans have a propensity to use whatever information is helpful, it is only natural that readers would use spelling constraints in letter and word perception. Studying the time course (dynamics) of word recognition allows us to address how the stimulus information from print is combined with the contextual information from orthographic structure.

There are two fundamentally different accounts of the WSE. One type of explanation is that the subject can use knowledge of spelling during letter and word perception. Processing the letter information is necessarily a time-extended process because information about the letters builds up gradually. The function describing this buildup appears to be a negatively accelerating growth function (Massaro, 1975a). Furthermore, because of the brief duration of the display or backward masking stimulus in a typical experiment, there is usually only partial information about the letters in the display even after processing is complete. Independently of the letter information, however, information about orthography can be exploited to reduce the number of alternative letters and to achieve a correct percept that is based on partial visual information. Like Estes and Brunn (1987), it is assumed that the orthographic context has no influence on the early feature stage of visual processing. Orthographic information does not have to be consciously known or applied, and it does not have to be perfect. Analogous to letter information, orthographic information can make a positive contribution to word recognition even though it is only partially informative. This explanation, within the context of the FLMP, states that readers have two sources of information given a word and only a single source given a single letter or a nonword. It should be noted that the FLMP also allows for a positive lexical contribution, but lexical information is not considered to be necessary for a WSE.

Another account of the word advantage dispenses with the idea of orthographic knowledge entirely and explains the word advantage simply in terms of the contribution of the specific words in the reader's lexicon (Brooks, 1978; Glushko, 1979). The most complete model within this class is the interactive activation model (IAM; McClelland & Rumelhart, 1981). The model was designed to account for context effects in word perception and postulates three levels of units: features, letters, and words. Features activate letters that are consistent with the features and inhibit letters that are inconsistent; letters activate consistent words and inhibit inconsistent words; and most importantly, words activate consistent letters (top-down feedback). In addition, activated words inhibit other words. Interactive activation explains the word advantage over nonwords in terms of interactive activation from the word level to the letter level. The FLMP and IAM make very similar predictions for asymptotic performance, and a more complex experiment is necessary to distinguish between them. Massaro and Cohen (1991) reanalyzed the results of several experiments to provide empirical tests between these two accounts of the word advantage. These tests are particularly informative because they measure the dynamics of information processing in a backward masking task.

Context Effects and Backward Masking

Massaro (1979) independently varied stimulus information and orthographic context in a backward masking task. It is possible to gradually transform the letter *c* into an *e* by extending the horizontal bar. To the extent the bar is long, there is good visual information for an *e* and poor visual information for a *c*. There were six different bar lengths between a prototypical *c* and a prototypical *e*. If this test letter is presented as the first letter in the context *-oin* and the context *-dit*, the orthographic context *-oin* favors *c*, whereas the context *-dit* favors *e*. In normal text, the letter *c* is more likely to occur in the first context and *e* is more likely in the second context. The context *-tsa* and *-ast* can be considered to favor neither *e* or *c*. The first remains an unlikely letter string whether *e* or *c* is present, and the second is orthographically well structured for both *e* and *c*. Four analogous contexts were used for presentations of the test letter in each of the other three positions of the four-letter string.

The experiment factorially combined the six levels of visual information with these four levels of orthographic context, giving a total of 24 experimental conditions (Massaro, 1979). The test letter was presented at each of the four letter positions in each of the four contexts. This study also evaluated context effects as a function of processing time controlled by the interval between the test display and a backward masking stimulus. The masking stimulus was composed of nonsense letters created by selecting random feature strokes from the letters of the alphabet (Taylor, Klitzke, & Massaro, 1978). Subjects were instructed to identify the test letter as *c* or *e* on the basis of what they saw.

Figure 2 gives the average probability of an *e* identification as a function of the stimulus value of the critical letter, the orthographic context, and the processing time. Both the test letter and the context influenced performance in the expected direction. Subjects were more likely to identify the letter as *e* to the extent that the letter resembled *e* and to the extent that *e* was supported by the orthographic context. Furthermore, the effect of orthographic context was larger for the more ambiguous test letters. Both the FLMP and the

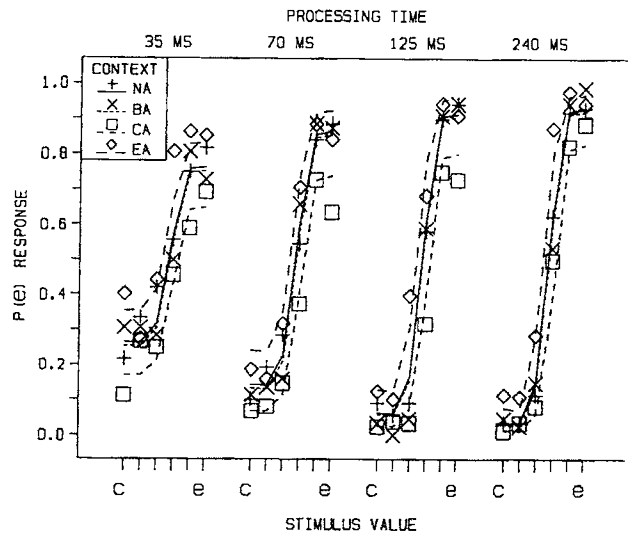

Figure 2. Observed (points) and predicted (lines) probability (P) of *e* identifications as a function of the bar length of the test letter, the orthographic context, and the processing interval between the onset of the test stimulus and the onset of the masking stimulus for the dynamic fuzzy logical model of perception. NA = neither admissable; BA = both admissable; CA = *c* admissable; EA = *e* admissable.

IAM are globally consistent with these effects. For the FLMP, the WSE reflects the evaluation and integration of the stimulus and contextual sources of information. For the IAM, the WSE is described by letter and word activations from the stimulus and contextual sources of information.

Performance was more chaotic (in the sense of being more random and giving a more restricted range of response probabilities) at the short masking intervals. That is, less processing time leads to less orderly behavior, as expected from research on the time course of perceptual processing. Even for prototypical test letters, subjects did not make consistent identification judgments at short masking intervals. According to the FLMP, there was not sufficient time for feature evaluation and integration to take place before the onset of the masking stimulus. According to the IAM, there was not sufficient time for letter and lexical activation before the onset of the masking stimulus.

Both the test letter and the context influenced performance at all masking intervals. The effect of test letter was attenuated at the short relative to the long processing time. That is, the identification functions covered a larger range across the *e–c* continuum with increases in processing time. The context effect was larger for the prototypical test letters at the short than at the longer masking intervals. This result follows naturally from the trade-off between stimulus information and context in the FLMP. Context has a larger influence to the extent the stimulus information is ambiguous. The exact prediction of the IAM is less obvious, but in general the context effect should be larger at long masking intervals because context eventually overwhelms the stimulus information (McClelland, 1991; McClelland & Rumelhart, 1981). The critical test, of course, is how well the models can describe all of the experimental conditions with a fixed set of parameters. Therefore, it is necessary to provide quantitative tests of the FLMP and IAM against these results.

Tests of the FLMP and IAM

Massaro and Cohen (1991) extended the FLMP to account for the time course of perceptual processing. The assumption was that feature evaluation would follow the same negatively accelerating growth function found in backward recognition masking tasks. The backward masking function can be described accurately by a negatively accelerated exponential growth function of processing time,

$$d' + \alpha(1 - e^{-\theta t}), \quad (1)$$

where d' is an index of resolution of the target. The parameter α is the asymptote of the function and θ is the rate of growth to the asymptote. The function putatively describes feature evaluation and can be conceptualized as representing a process that resolves some fixed proportion of the potential information that remains to be resolved per unit of time. The same increment in processing time results in a larger absolute improvement in performance early relative to late in the processing interval.

Following the theoretical analysis of backward masking, a masking stimulus would terminate any additional processing of the test stimulus. The dynamic model given by Equation 1 can be combined with the FLMP to describe how multiple sources of information are evaluated and integrated over time. As shown in Figure 1, the output from evaluation is fed continuously to the integration process. The outputs from integration are fed forward to the decision process, which computes the relative goodness of match of the alternatives. In the backward masking task with unlimited response time, it seems reasonable to assume that the decision is not made until evaluation and integration of these two sources of information are as complete as possible. Of course, shorter masking intervals will allow less time for evaluation and integration. Figure 2 illustrates that less processing time leads to less orderly behavior—as expected from research on the time course of perceptual processing.

This dynamic FLMP was tested against the results (Massaro & Cohen, 1991). Given the four masking intervals in the task, it is possible to describe performance in terms of the changes in featural information and orthographic context across the four masking intervals. Eleven free parameters are required for the fit of the FLMP: the rate of growth of the functions and 10 asymptotic values for the 10 functions from the 6 levels of stimulus information and the four levels of context. The fit of the model was very good; the root-mean-square deviation (RMSD) between the observed and predicted points was .0501. The lines in Figure 2 give the predictions of the FLMP.

Massaro and Cohen (1991) also fit a variety of stochastic IAMs to the data (see McClelland, 1991). To bring the IAM in line with the empirical results of Massaro (1989), McClelland (1991) modified the original IAM by allowing variability at the input or during each processing cycle and changing the decision rule from a relative goodness rule to a best-one-wins rule. The topology of the network tested by Massaro and Cohen (1991) was designed to account for the effects of both the target letter and the orthographic context in the Massaro (1979) study. Figure 3 shows that three layers of units were used: context, target, and word. There were two-way connections between the context and word units and the target and word units to reflect interactive activation. It was also assumed that the mask terminated further processing, as in the fit of the dynamic FLMP. This model also required 11 free parameters—10 for the inputs corresponding to the 6 levels of stimulus and 4 levels of context, and 1 for the translation of processing time into the number of processing cycles. The RMSD obtained for this model was .1135, about twice as large as that found for the dynamic FLMP. Thus, the orthographic-context account of the FLMP gives a much better description of the results than the specific-word account of interactive activation.

These results provide a dramatic falsification of interactive activation to account for word recognition in reading. In the IAM, context modifies the representation of the target letter. As shown by the good description given by the FLMP, however, the perceptual advantage for letters in words can be explained in terms of the word context functioning as an additional independent source of information. The IAM also falsely predicts that the influence of context must occur later during perceptual processing than the influence of stimulus information. Contrary to IAM, the FLMP accurately predicts that the influence of context does not necessarily lag behind the influence of stimulus information. These experimental results agree with our reading experience. In the IAM, slow reading means long processing times in which the context can overwhelm the stimulus information about the target letter. In contrast, we read slowly to detect spelling errors, which shows that information about the target letter can remain immune to the context. We recognize letters better in words than in nonwords simply because we recognize words better than nonwords (due to orthographic and perhaps lexical constraints), not because activation of the letter is somehow modified differently in word relative to nonword contexts.

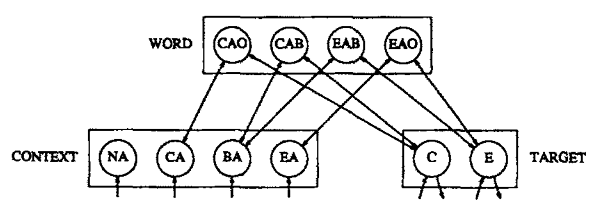

Figure 3. Network used in the simulation of the interactive activation model applied to the experiment of Massaro (1979) with the target letters *e* and *c*. The units are CAO (*c* admissible only), CAB (*c* admissible both), EAB (*e* admissible both), EAO (*e* admissible only), NA (neither admissible), CA (*c* admissible), BA (both admissible), EA (*e* admissible), C (*c*), and E (*e*). The inhibitory connections between units within the word, context, and target levels are not shown in the network.

Word Superiority Effect (WSE)

The findings of Massaro (1979) reveal a bias or tendency to identify a letter that is supported by both stimulus information and context. The word superiority effect, on the other hand, shows that subjects are more accurate in identifying letters supported by stimulus information and context. We claim that these two results are outcomes of the same processes. Early findings revealed that words give an accuracy advantage to the letters that make them up. Psychologists were suspicious of these results because post hoc guessing and memory might be responsible for the results. The Reicher–Wheeler task (Reicher, 1969; Wheeler, 1970) supposedly controls for these contributions. A short target display is followed by two test alternatives. For example, the target *WORD* is presented, with the two test alternatives (*D* and *K*) for the fourth position. Guessing a letter that makes a word will not help because both alternatives, *D* and *K*, can be added to *WOR*__ to form words. Of course, a different word is presented on each trial, and the subject does not know which letter position will be tested until the cue appears. Performance in this condition is compared with performance when the subject is presented with a single letter at any of the four letter positions defined by the word. In our example, the subject is presented with *D* alone and asked whether it was *D* or *K*. The word–letter comparison precludes a memory advantage for the word condition. A third condition is a nonword that does not conform to the spelling rules of English: for example, *OWRD* or *OWRK*. Performance in the task gives a word advantage over nonwords and sometimes over single letters. In Reicher's (1969) experiment, subjects picked the correct alternative 12% more often when faced with a word display than when tested with a nonword or single-letter display.

Within the context of the FLMP, visual information and orthographic context are integrated so that performance is influenced by both these sources of information. Consider the contrast of a test word *WORD* with a test nonword *ORWD*. In both cases, the two test alternatives are *D* and *K* for the fourth position. If the subject has no visual information about the test string, there would be no advantage in the word relative to the nonword condition. However, if a curved feature on the right half of the fourth letter was derived from the visual information, then the candidates for this position might be *D*, *O*, or *Q*. If the first three letters *WOR* were also recognized in the test word, then orthographic context would eliminate the candidates *O* and *Q*, leaving *D* as the only perceptual alternative. Recognizing *ORW* in the nonword condition would not constrain the alternatives for the fourth position, thus making perception of any of the three alternatives equally likely. The advantage of words over nonwords in the Reicher–Wheeler task results from this contextual difference. The Reicher–Wheeler control does not eliminate a possible influence of orthographic context during perception. The control simply precludes a postperceptual guessing advantage for words because both response alternatives spell words.

In the IAM, a WSE occurs because top-down connections from the word level to the letter level allow context to modify the representation at the letter level. Although the model can account for many of the existing results on the WSE, it is important to stress that interactive activation is not necessary to account for these results; adequate accounts of the WSE were available before the IAM was published. The FLMP, for example, does so without interactive activation. Furthermore, data in the literature falsified the assumption of interactive activation before the IAM was published. In the FLMP, context operates independently of featural analyses, simply by providing an additional source of information (Massaro, 1984). Massaro and Cohen (1991) provided a strong quantitative test of the FLMP's description of the WSE by a reanalysis of Massaro and Klitzke (1979).

Backward Masking, Lateral Masking, and the WSE

Massaro and Klitzke (1979) used four types of display in the Reicher–Wheeler task: words, nonwords, letters, and letters flanked by dollar signs. On each trial, one of these test displays was presented alone or followed by a masking display after one of seven stimulus onset asynchronies (SOAs). Two choice alternatives were presented ¼ s after the test display as in the standard Reicher–Wheeler control. The masking stimulus varied from trial to trial and was composed of nonsense letters created by selecting random feature strokes from the letters of the alphabet.

Figure 4 gives the probability of correct recognition of the test letter as a function of processing time and orthographic context. The results indicated that performance under all

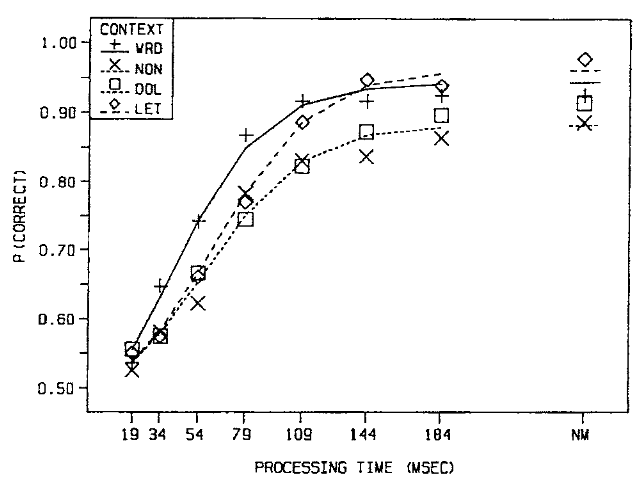

Figure 4. Observed probability (P; in points) of correct identification of the test letter as a function of processing time for the letter-alone (LET), word (WRD), nonword (NON), and letter-in-dollar-signs (DOL) contexts. The lines are the predictions of the fuzzy logical model of perception. The solid line gives the predictions for the word context, the large dashed line for the letter-alone condition, and the small dashed line for the nonword and letter-in-dollar-signs contexts. Note that both the observations and the predictions give a crossover between the word and letter-alone conditions (results after Massaro & Klitzke, 1979; predictions from Massaro & Cohen, 1991). NM = no-mask condition.

conditions improved with increases in processing time. The advantage of words relative to letters at short processing times was reversed at long processing times. Performance for nonwords and letter in dollar signs was poorest at all processing intervals. These results show the influences of stimulus information, orthographic context, and lateral masking. Because of the lateral interference of adjacent letters on each other, the sensory information in the word, nonword, and letter-in-dollar-signs conditions must necessarily be less than the single-letter condition. The word condition still has the advantage of orthographic context, whereas the other three types of display do not. Lateral masking and orthographic context must necessarily counteract each other, and only a quantitative model incorporating both of these contributions can be reasonably tested against the results.

The dynamic FLMP not only predicts a WSE, it predicts a subtle interaction between the WSE, backward masking, and lateral masking. A nonword provides only a single source of information about the test letter. A word provides two sources of information. The FLMP predicts that two sources of information can lead to better performance than just one. Thus, more information will be accumulated over time for the word than for the nonword displays. The single-letter versus word displays more complex, however. The advantage of orthographic context in the word condition is counteracted by lateral masking. The relative magnitude of these counteracting influences necessarily varies with processing time because the amount of the letter information varies with processing time. This model predicts (a) word advantage over single letters with a masking stimulus at short SOAs and (b) no word advantage over single letters at long SOAs or when no mask is presented.

The interaction of the WSE with SOA is an important result because it reflects the interaction of a contextual (cognitive) influence with two sensory influences (perceptual processing time and lateral masking). Massaro and Cohen (1991) showed that the dynamic FLMP captures the observed results in a direct and parsimonious manner by accounting for the influences at the appropriate levels of processing. The components of the FLMP reflect the contributions of lateral masking, backward masking, and orthographic context. Given the importance of these findings, it is valuable to replicate and extend the results. Thus, the experiment was replicated with three different types of masking stimulus. As pointed out by Estes and Brunn (1987), the nature of the masking stimulus in the word recognition task has not received the experimentation it deserves. According to these authors, the nature of the mask should influence the word advantage. Mask characters that compete with target letters for access to working memory but do not interfere with the recognition of familiar letter groups should give the largest word advantage.

Johnston and McClelland (1980) found that the word advantage of letters in words relative to single letters was reduced with a letter mask compared to an artificial character mask. As pointed out by Jordan and de Bruijn (1993), however, these earlier studies confounded the size of the mask with the letter and word conditions. The same mask was used in all conditions, with the result that the relative size of the mask display to the test display was much greater for the letter than the word conditions. Therefore, it is necessary to study the nature of the mask without a confounding of the relative size of the test and mask displays. Massaro and Klitzke (1979) eliminated this confounding by equating the size of the mask with the size of the test display. A single character mask was used in the letter condition and four mask characters were used in the other three test conditions. The fragment mask was made up of one or four nonsense characters, each made by a random juxtaposition of the features making up the individual letters. Although the individual features were randomly displaced to occupy a different location in the nonsense character than in the actual letters, the average size of the fragment-mask nonsense character never exceeded the average size of the test letter.

Experimental Study of WSE with Different Masks

To address the influence of the nature of the mask on the word advantage, we replicated the Massaro and Klitzke (1979) experiment with three types of masks: nonsense characters, letters, and words. The nonsense character mask was the same as that used by Massaro and Klitzke. A single letter could be masked by a nonsense character or a single letter. Words, nonwords, and letters presented in dollar signs could be masked by a string of nonsense characters, a string of random letters, or an actual word. The masking stimulus varied from trial to trial with these constraints. According to the hierarchical model of Johnston and McClelland (1980), the letter and word masks should lead to a smaller word advantage than the nonsense-character mask. They assume that a nonsense-character pattern mask produces a WSE because the nonsense characters are not directly connected to the word nodes, and the higher word level detector remains active long after the deactivation of all the letter detectors. A letter or word mask should greatly reduce the WSE because the masking letters should activate word detectors inconsistent with the target word. Estes and Brunn (1987) make a similar prediction, because the mask letters would compete with target letters for access to working memory but would not interfere with familiar letter groups or words.

Method

The new experiment replicated Massaro and Klitzke (1979) with four types of display in the Reicher–Wheeler task: words, nonwords, letters, and letters flanked by dollar signs. On each trial, one of these test displays was presented followed by a masking display after one of seven SOAs, or no mask was presented. Two choice alternatives were presented 250 ms after the test display as in the standard Reicher–Wheeler control.

The intensity of the test letters was varied between blocks of trials throughout the experiment to keep overall performance at 75% correct. Each condition was tested equally often with the same intensity level. Given that subjects got much better in the task over the course of the experiment, it was necessary to continually lower the intensity of the test stimulus throughout the experiment. Thus, although the intensity of the test and mask were initially equated, the masking stimulus was significantly more intense than the test stimulus during the major portion of the experiment. (This difference in intensity becomes important in the application of a dynamic model to the results.)

Seven subjects were tested. There were 40 observations per subject at each of the 96 conditions (4 contexts × 3 masks × 8 masking conditions). The duration of the test stimulus was 33 ms, as was the duration of the mask. The seven SOAs were 35, 45, 55, 75, 95, 125, and 155 ms, and there was a no-mask condition. There were 24 unique test items (or 12 pairs) at each of the 4 different contexts. Examples of the test items are given in Massaro and Klitzke (1979). The percentage correct judgments were pooled across subjects, giving a total of 280 observations per condition.

Results

The overall results reveal an unexpected barrier to answering the question of whether mask type modulates the WSE. As was noted in the *Method* section, overall performance was maintained at roughly 75% correct. Performance with a fragment mask was significantly better than performance with either a word or nonword mask. This difference occurs at all masking intervals, but it is primarily reflected in performance at the four shortest SOAs. Performance at the four shortest SOAs was 71.7% correct with the fragment mask and 59.2% correct with the word and nonword masks. Therefore, we cannot assume that the Mask Type × Test Type interactions are meaningful when accuracy is used as the dependent measure. Because of the overall performance differences due to mask type, differences in accuracy among different conditions cannot be assumed to be an interval scale of measurement (Loftus, 1978). Given that performance with the word and nonword masks is near chance at the short SOAs, it should not be surprising or theoretically interesting that the WSE is smallest at these conditions (a floor effect). To overcome these limitations, a mathematical model analysis will be used instead of an analysis of variance. As will be seen, the advantage given by the fragment mask is described in terms of a short period of integration allowing somewhat more processing time relative to the word and nonword masks.

The points in Figures 5, 6, and 7 present the probability of a correct identification as a function of the test display and the theoretical processing time for the three types of masks. The performance advantage with the fragment mask can be seen in the differences in Figures 5 and 6 relative to Figure 7. It appears that a mask composed of letters is a more effective mask than one composed of random characters made of letter features. The nonsense character mask may have been less effective because the letter features were displaced in this mask relative to their position in the letters themselves. Because of the greater potential for spatial overlap between the test and mask, the letter mask might have been more effective in terminating perceptual processing of the test display. We describe this effect in the FLMP by allowing a small amount of additional processing time after the mask is presented for the nonsense character mask relative to the letter and word masks.

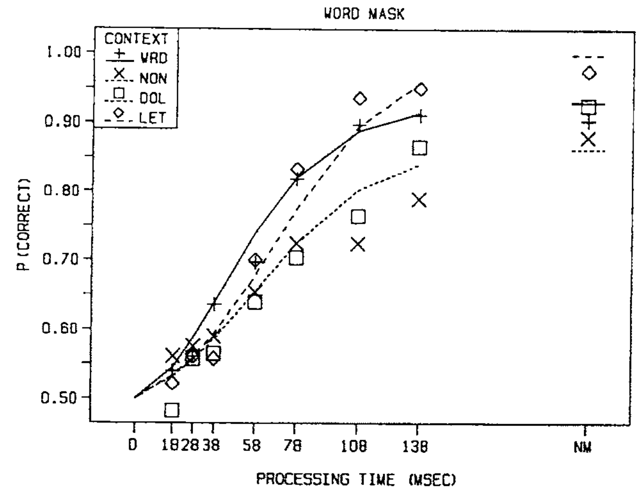

Figure 5. Observed probability (P; in points) of correct identification of the test letter as a function of theoretical processing time for the letter alone (LET), word (WRD), nonword (NON), and letter in dollar signs (DOL) contexts in the word mask condition. The lines are the predictions of the fuzzy logical model of perception. The solid line gives the predictions for the word context, the large dashed line for the letter-alone condition, and the small dashed line for the nonword and letter-in-dollar-signs contexts. Note that both the observations and the predictions give a crossover between the word and letter-alone conditions. NM = no-mask condition.

Of theoretical interest is whether the WSE is larger for the letter masks relative to the nonsense character mask. As can be seen in Figures 5–7, the masking functions were very similar across the three masking conditions. Although there is an overall performance advantage with the fragment mask, the differences due to mask type are the same across changes in processing. There is a word advantage over nonwords and a letter embedded in dollar signs. In addition, there is a crossover in the word and single-letter conditions, with an advantage for words at shorter processing times and an advantage for single letters at longer processing times. This result holds in the important case in which the size of the masking stimulus is not confounded with the type of display (Jordan & de Bruijn, 1993). We now show how the dynamic FLMP can account for the results.

Test of the Dynamic FLMP

Given the lateral interference of adjacent letters on each other, the sensory information in the word, nonword, and letter-in-dollar-signs conditions must necessarily be less than the single-letter condition. Furthermore, the asymptotic test letter information must necessarily be less in the word, nonword, and letter-in-dollar-signs conditions relative to the single-letter condition. Of course, the word condition still has the advantage of orthographic context, whereas the other three types of display do not.

In the FLMP model, given a single test letter or a nonword, only a single source of information is evaluated, until the onset of the masking stimulus or until its representation

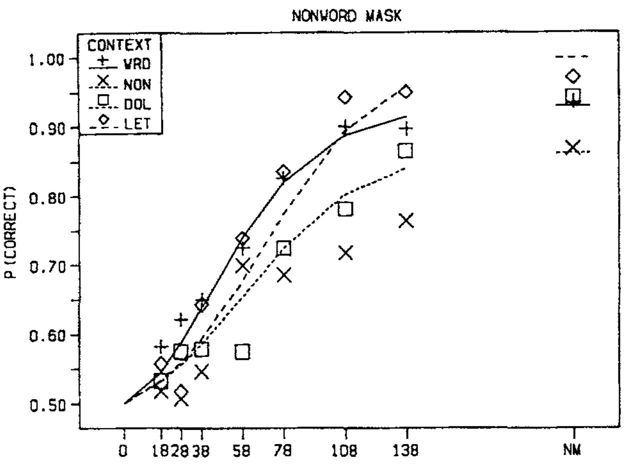

Figure 6. Observed probability (P; in points) of correct identification of the test letter as a function of theoretical processing time for the letter-alone (LET), word (WRD), nonword (NON), and letter-in-dollar-signs (DOL) contexts in the nonword mask condition. The lines are the predictions of the fuzzy logical model of perception. The solid line gives the predictions for the word context, the large dashed line for the letter-alone condition, and the small dashed line for the nonword and letter-in-dollar-signs contexts. Note that both the observations and the predictions give a crossover between the word and letter-alone conditions. NM = no-mask condition.

is no longer present in a preperceptual visual storage. Given a test word, two sources of information are evaluated and integrated over time until the onset of the masking stimulus or until the representation of the test stimulus is no longer present in preperceptual visual storage. Thus, the test word will tend to accumulate more information over time than the test letter, and a WSE should be observed. The potential visual information that could be derived from the display given unlimited processing time must also necessarily differ for the letter and word displays. Lateral masking (the mutual interference between adjacent letters in a display) serves to diminish the asymptotic information available from the test letter in the word relative to the letter display.

Given that the masking stimulus was significantly more intense than the test stimulus, it is reasonable to assume that the masking stimulus was transduced by the visual pathways more quickly than was the test stimulus and that the SOA probably overestimates the perceptual processing time available before the onset of the masking stimulus. To account for this effect in the fit of the dynamic FLMP, a dead time during which no processing occurred was estimated and subtracted from the SOA.

The mathematical form of the FLMP model assumes, first of all, asymptotic support for the correct letter given the feature information of the letter, α_{let}, and asymptotic support for the correct letter given context information, α_C. In addition, we assume that asymptotic support for the correct response letter in a word, nonword, or dollar sign context, α_{wnd}, is less than α_{let} due to lateral masking. Following Massaro and Cohen (1991), these sources of information at a particular processing time, F_{let}, F_{wnd}, and C, develop with processing time from an initial neutral value of .5 to their asymptotic values, as given in their Equations 27–29:

$$F_{let} = \alpha_{let}[1 - e^{-\theta(t - t_{dead})}] + .5[e^{-\theta(t - t_{dead})}], \quad (2)$$

$$F_{wnd} = \alpha_{wnd}[1 - e^{-\theta(t - t_{dead})}] + .5[e^{-\theta(t - t_{dead})}], \quad (3)$$

$$C = \alpha_C[1 - e^{-\theta(t - t_{dead})}] + .5[e^{-\theta(t - t_{dead})}], \quad (4)$$

where t is processing time (SOA), t_{dead} is initial dead time, and θ is the rate of processing. The no-mask condition resembles a masking condition at a long SOA (in this case, we assumed an infinite SOA, and it follows that $F_{let} = \alpha_{let}$, $F_{wnd} = \alpha_{wnd}$, and $C = \alpha_C$).

We assume that the support for an incorrect letter is given by the complement of its support for the correct letter. Thus, if x is the support for a correct letter, $1 - x$ (written $\bar{x}$) is the support for the incorrect letter. On a given trial, for example, the possible letter responses allowed might be *D* and *K*, with *D* being the correct response. If we have a word context, which supports both response alternatives, the support given the correct alternative will be the conjunction of the two sources C and F_{wnd}, whereas the incorrect response will be supported by the conjunction of C and $\overline{F_{wnd}}$. The other 24 letters of the alphabet, represented as a group by the symbol *X*, will each be supported by the conjunction of $\bar{C}$ and $\overline{F_{wnd}}$. (We note parenthetically that this representation of the other 24 letters is only approximately true. If the first three letters are recognized as *WOR*, for example, then some

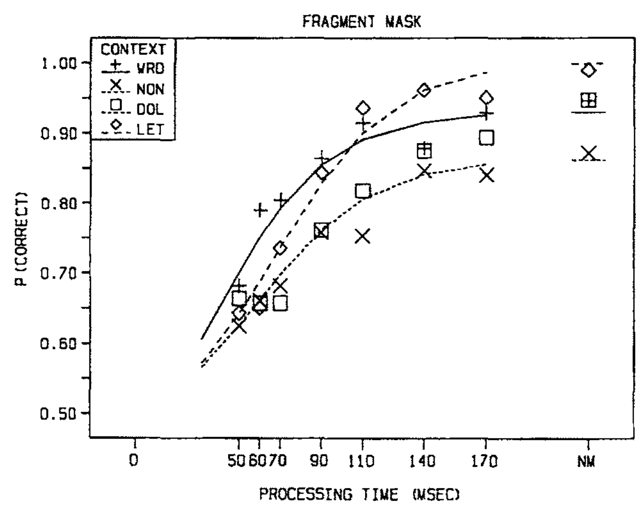

Figure 7. Observed probability (P; in points) of correct identification of the test letter as a function of theoretical processing time for the letter-alone (LET), word (WRD), nonword (NON), and letter-in-dollar-signs (DOL) contexts in the nonsense character mask condition. The lines are the predictions of the fuzzy logical model of perception. The solid line gives the predictions for the word context, the large dashed line for the letter-alone condition, and the small dashed line for the nonword and letter-in-dollar-signs contexts. Note that both the observations and the predictions give a crossover between the word and letter-alone conditions. NM = no-mask condition.

other letters—such as *M*—should also be supported by the word context. Similarly, some other letters may be supported by the letter feature information.) As in other applications of the FLMP we will use multiplication to carry out conjunction. Massaro and Cohen (1991, Equations 30–38) show how Equations 2–4 were used and how the integration algorithm of the FLMP predicts the probabilities of perceiving the correct letter, the incorrect alternative, and any other of the 24 letters. To predict performance in the Reicher–Wheeler control, an additional assumption is needed. Thompson and Massaro (1973) found evidence for the assumption that subjects perceive the display before consideration of the two test alternatives. If one of the test alternatives agrees with what they saw at that position, they choose it. Otherwise, they guess randomly between the two alternatives. This assumption has also been used by other researchers (McClelland, 1991).

The fit of the FLMP for the results is identical to the fit of Massaro and Cohen (1991), except for an additional processing time for the fragment mask condition:

$$F_{\text{let}} = \alpha_{\text{let}}[1 - e^{-\theta(t - t_{\text{dead}} + t_{\text{INT}})}] + .5[e^{-\theta(t - t_{\text{dead}} + t_{\text{INT}})}], \quad (5)$$

$$F_{\text{wnd}} = \alpha_{\text{wnd}}[1 - e^{-\theta(t - t_{\text{dead}} + t_{\text{INT}})}] + .5[e^{-\theta(t - t_{\text{dead}} + t_{\text{INT}})}], \quad (6)$$

$$C = \alpha_{\text{C}}[1 - e^{-\theta(t - t_{\text{dead}} + t_{\text{INT}})}] + .5[e^{-\theta(t - t_{\text{dead}} + t_{\text{INT}})}], \quad (7)$$

where t_{INT} is the additional processing time that occurs during a period of integration beginning with the fragment mask presentation. For the word and nonword masks, t_{INT} is assumed to be 0. It is only with the fragment masks that integration is assumed to occur, and t_{INT} takes on a positive value. To test this idea, the data from the three masking conditions were fit simultaneously, using the same parameters α_{let}, α_{wnd}, α_{C}, θ, and t_{dead} (having values .9999, .9854, .7121, 34.75, and 3.4 ms, respectively). In this case, the overall RMSD was .0564. When the additional t_{INT} parameter was added to the model, the RMSD fell to .0337 with the best fitting parameters for α_{let}, α_{wnd}, α_{C}, θ, and t_{dead} having values .9999, .9858, .7214, 36.18, and 16.9 ms, respectively. The additional t_{INT} parameter was 32.1 ms. Making use of the Akaike information criterion (AIC) statistic to compare these two models (Akaike, 1974), we computed the AIC for each model (see Massaro & Cohen, 1991). This formal theory takes into account the likelihood of a model fit and also the number of parameters used by the model. Smaller AIC values are preferred. The AIC for the first model was 1094 versus 832 for the second model, so the latter model with t_{INT} is a statistically significant improvement, even taking into account the additional parameter.

To provide a statistical test of whether the type of mask influenced the WSE, an additional model was fit to the results. This model assumed that α_{C} could differ as a function of mask. That is, if the nature of the mask modulates the WSE, then the contextual support for the test letter, α_{C}, should differ as a function of mask. Adding two additional parameters to allow an effect of mask type improved the fit of the model an insignificant amount from .0337 to .0334. The best fitting parameters for α_{let}, α_{wnd}, θ, and t_{dead} were .9999, .9857, .7214, 36.38, and 16.7 ms, respectively. The t_{INT} value was 30.8 ms. The α_{C} values were .6790, .7290, and .7483 for the word, letter, and fragment masks, respectively. Using the parameter values of α_{C} as an index of the WSE, the magnitude of their differences gives a measure of importance of mask type for the WSE. By this criterion, mask type appears to modulate the influence of orthographic context by only 9%. The AIC value (833) for the model assuming an effect of mask type was actually larger than the value (832) for the model assuming no effect of mask type. Thus, we have statistical support for the hypothesis that mask type is not critical for the WSE.

The lines in Figures 5–7 give the predictions of the six-parameter FLMP to the results. The FLMP predicts that two sources of information can lead to better performance than just one. If the visual information about the test letter is presented in a word or nonword context, an advantage for words (.792) over nonwords (.705) is predicted. This prediction is consistent with the results shown in Figure 4. At asymptote for these parameter values, the letter presented alone (.895) gives better performance than a letter presented in a word (.792). As can be seen in Figures 4–7, the model also predicts a word advantage over single letters with a masking stimulus at short SOAs but not at long SOAs and when no mask is presented. As can be seen in Figures 4–7, the dynamic FLMP predicts the interaction between the WSE and SOA, without any arbitrary assumptions. The assumption of two sources of information in the word condition relative to just one in the letter condition is necessitated by the model. The assumption that the presence of lateral masking in the word condition but not the letter condition influences the potential information of the test letter (α_{let}) is consistent with the literature on visual information processing. These two constraints are responsible for the variation in the WSE with differences in processing time in the Reicher–Wheeler task.

Figures 5–7 also show the observed (points) and predicted (lines) performance in the nonword and letter-in-dollar-signs conditions. Performances in these displays suffer because of lateral masking and do not benefit from orthographic context. These results substantiate the predictions of the word and letter displays because they were predicted using the same free parameters values that were used to describe the letter and word conditions.

Discussion

The results indicated that the WSE is necessarily modulated by lateral masking and processing time, but not the nature of the masking stimulus. The FLMP accurately described how letter information and context are processed in real time to determine performance. The dynamics of information processing along with the joint influence of several sources of information are nicely described by the FLMP.

In terms of how an IAM might work for these same data, McClelland and Rumelhart (1981) offered a different interpretation of the interaction of the WSE and backward masking. They assumed that the nature of the perceptual processing was the same for the mask and no-mask conditions. However, the subject's decision would be made at different times after the onset of the displays. (McClelland and Rumelhart, 1981, correctly acknowledge that the assumption of different readout times for the mask and no-mask conditions is reasonable only when these two conditions are tested in different blocks of trials. In the current study, however, all of the masking conditions were varied randomly within a block of trials.) For the no-mask condition, the decision was made after 50 cycles of processing, and the model predicted a 10% advantage of words over single letters. For the masking condition, the decision was made after 15 cycles of processing, and a 15% WSE was observed. This simulation does not predict a single-letter advantage over a letter when no mask is present, as found in the present experiments. Thus, the original explanation given by the IAM would have to be drastically modified in order to describe the quantitative results in Figures 4–7. In addition, we expect the IAM to have difficulty predicting the dynamics of performance—as it did in the *e–c* experiment.

In the present experiment, we found no support for the prediction of Estes and Brunn (1987) and Johnston and McClelland (1980) that letter and word masks should reduce the WSE. Eliminating the confounding of size of the mask in previous studies, we find no change in the WSE with feature, letter, and word masks. Thus, the hierarchical representation explanation of Johnston and McClelland (1980) and the working memory explanation of Estes and Brunn (1987) cannot account for the WSE in the present experiment. The best explanation is that the word context functions as an additional source of information, giving an advantage over nonword and single letters.

A good deal of concern has been voiced about the nature of the stimulus conditions that are necessary to produce a WSE. Furthermore, theories of the WSE have been proposed that claim necessary stimulus conditions for a WSE. This tack seems inappropriate given the robustness of the WSE. Rather, a theory would be better framed with the caveat cerebus parus—all else constant or unvarying. With respect to the robustness of the WSE, an advantage of processing letters in words relative to letters in random letter strings has been demonstrated in a variety of experimental situations (Massaro, 1980). As a recent example, Jordan and Bevan (1994) found the same WSE (words over isolated letters) for both forward and backward masks. Thus, it seems unproductive to try to craft a narrow explanation of the WSE in terms of a set of specific stimulus conditions, such as the necessary condition of a backward mask (Johnston & McClelland, 1980).

In addition to the variety of positive findings in the Reicher–Wheeler task, a WSE has been found in several other tasks. One task is a target search task in which a subject determines whether a target letter is present in a test string of letters. In an early study, Krueger (1970) had subjects search through a list of six-letter words or nonwords. Search time was roughly 20% faster for words than nonwords. A similar advantage was found for common over rare words and for rare words over pseudowords. Mason (1975) found that good readers were faster in letter searches through strings with high rather than with low positional letter frequency. Massaro, Venezky, and Taylor (1979) found that orthographic structure facilitated letter search both in time and accuracy. Krueger and Shapiro (1979) had subjects monitor a list of items presented one item at a time at varying rates of presentation. In one task, subjects had to indicate whether a mutilated *A* or a mutilated *E* appeared in the list. Performance was more accurate for word lists than for nonword lists. Subjects supposedly could read the letters more quickly in the word lists and, therefore, recognize which letter was mutilated more accurately. More recently, Prinzmetal (1992) demonstrated that the WSE does not require a T-scope (i.e., a short display). When letter strings were made more difficult to see, either by decreasing the size of the type or embedding the letters in a simultaneously present pattern mask, a WSE was observed. Prinzmetal's (1992) conclusion resonates with the theme of this article. Drawing an analogy with object and depth perception, he observed that "we may use several sources of information for recognizing letters in words" (p. 483). In the next sections of this article, we analyze several other reading phenomena. Given that these phenomena use reaction time (RT) as the primary dependent variable, we extend the FLMP framework to account for RT as well as accuracy and perceptual report.

Extending the FLMP to Predict RT

An important dependent measure in reading research is RT in pronunciation and lexical-decision tasks. To date, the FLMP has been limited to predictions of proportion choice and accuracy. It is important to extend the model to predict RTs in order to test the model against a broader range of phenomena. The goal of this section is to develop the FLMP to account for RT results. The following section then evaluates the contribution of multiple sources of information to RT. With respect to the stage model in Figure 1, evaluation and integration are processes that occur over time, but the time required for evaluation and integration should not vary with the particular configuration of the sources of information available. Rather, the time for decision increases with the ambiguity of the information available to the decision stage (Massaro, 1987). For pedagogical purposes, the FLMP's predictions of identification and RT will be formalized within a bimodal speech perception task.

There is valuable and effective information afforded by a view of the speaker's face in speech perception and understanding. Visible speech is particularly effective when the auditory speech is degraded because of noise, bandwidth filtering, or hearing impairment. As an example, the perception of short sentences degraded by noise or filtering improves dramatically when subjects are permitted a view of the speaker. This same type of improvement has been observed in hearing-impaired listeners and patients with cochlear implants (Massaro, 1987). The strong influence of visible speech is not limited to situations with degraded auditory input. A perceiver's recognition of an auditory–visual syllable reflects the contribution of both sound and sight. If an auditory syllable /ba/ is dubbed onto a videotape of a speaker saying /da/, subjects often perceive the speaker to be saying /ða/.

In a typical experiment, the test procedure is an auditory–visual expanded factorial design (Massaro & Cohen, 1990) using unimodal and bimodal test trials. A five-step auditory /ba/ to /da/ continuum was synthesized by altering the parametric information specifying the first 80 ms of the consonant–vowel syllable. Using an animated face, control parameters were changed over time to produce a realistic visible articulation of a consonant–vowel syllable. By modifying the parameters appropriately, a five-step visible /ba/ to /da/ continuum was synthesized. These five levels of audible speech are crossed with the five levels of visible speech. The audible and visible speech also are presented alone giving a total of 35 (25 + 5 + 5) independent stimulus conditions. In one cross-linguistic study, the speech stimuli were varied between /ba/ and /da/ (Massaro, Tsuzaki, Cohen, Gesi, & Heredia, 1993). The presentation of the auditory synthetic speech was synchronized with the visible speech for the bimodal stimulus presentations. All of the test stimuli were recorded on video tape for presentation during the experiment. Six unique test blocks were recorded with all 35 test items presented in each block. Each subject was tested 4 times through the tape for a total of 24 observations for each of the 35 experimental conditions. Subjects were instructed to listen to and watch the speaker, and to identify the syllable as either /ba/ or /da/.

The points in Figure 8 give the average results for a group of 21 American native English-speaking subjects in the experiment. As can be seen in the figure, both the auditory and visual sources influenced identification performance. There was also a significant interaction because the effect of one variable was larger to the extent that the other variable was ambiguous.

To describe the results, the important assumption of the FLMP is that the auditory source supports each alternative to some degree and analogously for the visual source. Each alternative is defined by ideal values of the auditory and visual information. Each level of a source supports each alternative to different degrees, which are represented by the feature values. The feature values representing the degree of support from the auditory and visual information for a given alternative are integrated following the multiplicative rule given by the FLMP. The decision operation gives the response by determining the relative goodness of match of the relevant response alternatives. The formal model, tested against the results, requires 5 parameters for the visual feature values and 5 parameters for the auditory feature values. The lines give the predictions of the FLMP. As can be seen in Figure 8, this model is able to capture the auditory and visual influences on identification performance. The RMSD for the fit of the identification judgments of the 21 individual subjects averaged .052.

Figure 9 shows the mean RTs for the 35 conditions, as a function of the levels of the auditory and visual information. RT tends to increase with increases in the overall ambiguity of the test stimulus. For the unimodal conditions, RT is

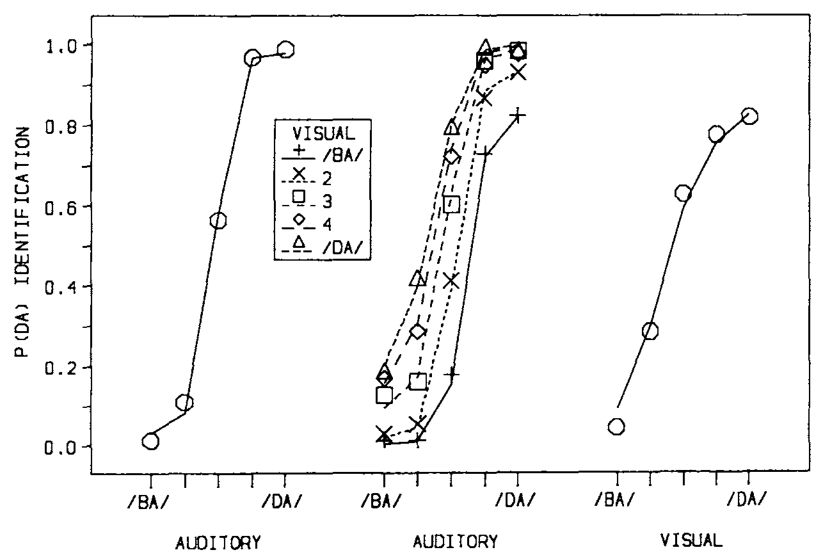

Figure 8. Mean observed (points) and predicted (lines) proportion (P) of /da/ identifications for the auditory-alone (left), the factorial auditory–visual (center), and visual-alone (right) conditions as a function of the five levels of the synthetic auditory and visual speech varying between /ba/ and /da/ for 21 American English speakers. The lines give the predictions for the fuzzy logical model of perception. (After Massaro et al., 1993.)

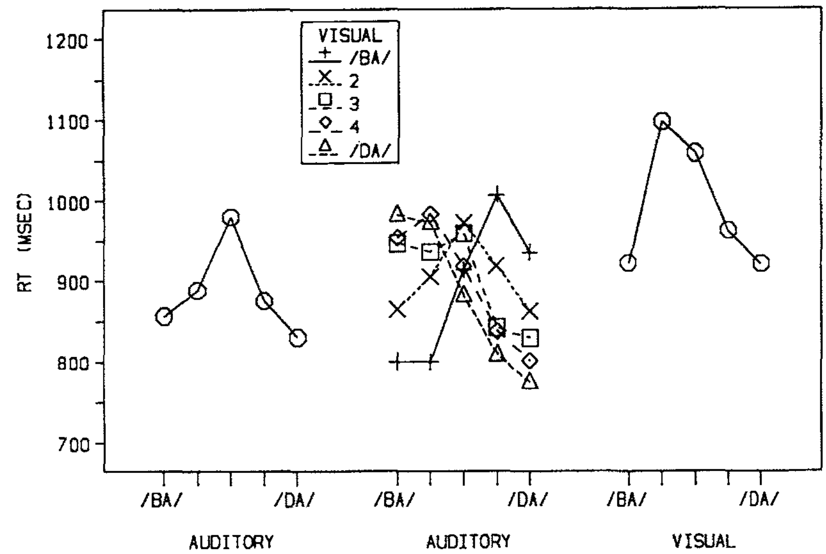

Figure 9. Mean identification RT (reaction time) for the auditory-alone (left), the factorial auditory–visual (center) and visual-alone (right) conditions as a function of the five levels of the synthetic auditory and visual speech varying between /ba/ and /da/ for 21 American English speakers.

longest in ambiguous middle range of the stimulus continuum. For the bimodal conditions, RT increases when both modalities are ambiguous or when the information from the two modalities differs.

To illustrate the predictions of the FLMP, consider the time required for the evaluation of a visual source of information V_j. It is assumed that this time does not depend on whether other sources of information are present or on whether the other sources agree or conflict with this visual source. Similarly, it is assumed that integration time does not depend on the number of sources of information or on whether the sources agree or conflict with one another. Thus, it is assumed that evaluation and integration processes consume time, but that this time is independent of the stimulus conditions.

Decision time, on the other hand, is assumed to be a direct function of the relative goodness-of-match (RGM) given by the relative goodness rule (RGR). The RGR gives the predicted probability of a response, in this case, *P*(/da/). Thus, the RT to a given speech event is assumed to be a function of *P*(/da/):

$$\mathrm{RT} = \mathrm{E} - f[P(/\mathrm{da}/)], \tag{8}$$

where E is some constant expected time for all processes not related to decision. Unfortunately, we do not know the function *f*. However, we get an idea of this function by looking at the relationship between RT and the probability of a particular response, *P*(/da/), in the two-choice identification task. The plus symbols in Figure 10 plot average RTs across subjects for /ba/ or /da/ responses as a function of *P*(/da/). This dependent measure is the average RT to each test condition regardless of the actual response given by the subject. Evaluating RT as a function of response type for each trial type is not feasible because one of the two responses could be very infrequent. As can be seen in the figure, RT increases as *P*(/da/) approaches .5 and diminishes as *P*(/da/) approaches 0 or 1.

This function appears to be linearly decreasing on each side of .5. If a linear function is assumed, the FLMP can be fit to the RTs by estimating *a* and *b* in the equation

$$\mathrm{RT} = a - b[|P(/\mathrm{da}/) - .5|], \tag{9}$$

where *a* and *b* are necessarily greater than or equal to zero, and $|x|$ means the absolute value of *x*. This model was fit to

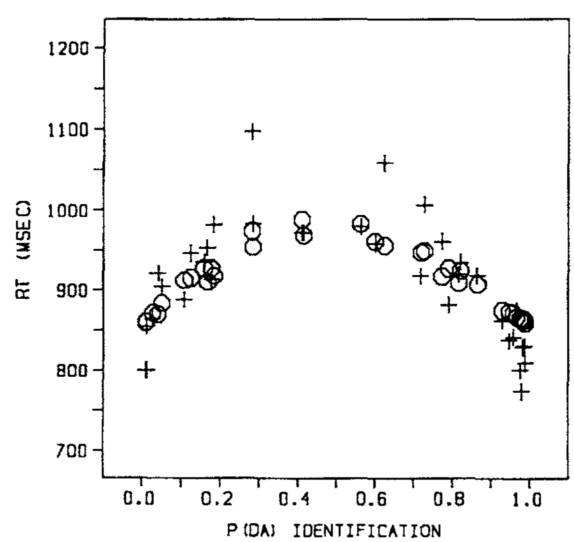

Figure 10. Mean observed (plus signs) and predicted (circles) reaction time (RT) as a function of P(/da/) identifications for 21 American English speakers.

each of the 21 subjects. First, the predicted *P*(/da/) values were taken from the FLMP fit of the identification judgments to the 35 stimulus conditions (see Figure 8). These predicted values were then used in Equation 9. Values of *a* and *b* were then estimated to maximize the fit of the RTs. The RMSD for the fit of the observed RTs averaged 84 ms. As can be seen in the Figure 10, the predictions of this model (represented by circles) provide a fairly good description of the changes in RT.

The FLMP describes the time course of evaluation and integration processes. Subjects are told to identify each test stimulus the best they can. Although they are not given any time pressure to respond quickly, the RTs are reasonably short given that many of the stimuli are ambiguous. Thus, we are confident that subjects are giving perceptual reports rather than problem solving. It is assumed that the goodness of match is continuously passed forward from the evaluation to the integration to the decision stage. The decision stage computes the RGM. An empirical finding is that RT increases to the extent that a subject responds equally often with the two response alternatives. In terms of the model, the time for the decision process increases to the extent that RGM is less extreme. It is assumed that the decision process waits until the RGM values reach asymptote (i.e., have a small change over some time period) and then chooses the appropriate response; that the decision stage probability matches in the sense that the relative frequency of a response is equal to the RGM; and that the time required for initiating a response is an increasing function of the ambiguity of the RGM. The decision process finds it more difficult to settle on a choice to the extent that the choices are less clear cut. This analysis of RT is in the spirit of other recent quantitative models (e.g., Link, 1992). Armed with this framework to describe RTs, we evaluate the hypothesis that there are multiple influences on letter recognition, ratings of how much a letter string looks like English spelling, naming, and lexical decision.

Multiple Influences in Reading Tasks

At first glance, the assumption that RT reflects primarily a decision stage appears to differ from the prototypical assumption that RTs supposedly reflect perceptual–linguistic processing. As an example, RTs are treated as the major independent variable in naming and lexical decision tasks, and the common assumption is that RTs are measuring perceptual and lexical access. An exception is research by Balota and Chumbley (1985), which addresses the role of decision processes in these tasks. A typical result is that RT decreases with increases in the information in the test stimulus. RTs have been shown to decrease with increases in word frequency (familiarity), orthographic structure, and spelling-to-sound regularity (Venezky & Massaro, 1987). These results can also be accounted for within the framework of the FLMP. Feature evaluation and integration will necessarily produce a less ambiguous RGM asymptote to the extent a given source of information is unambiguous or to the extent that there are multiple sources of information that are consistent with one another. The important result is that the RGM for the correct alternative will be larger with more information. Thus, RTs will necessarily be faster to the extent there are several sources of information supporting the correct alternative. The reasonably good prediction of the RTs provides support for the description given by the FLMP (see Figure 10). More generally, the FLMP prediction is that RT will be linearly related to the ambiguity of a test stimulus. In naming and lexical-decision tasks, RT should be a positive linear function of the ambiguity of the test word. We now analyze the role of neighborhoods and spelling-to-phonology influences in letter and word recognition.

Good and Bad Neighbors

An influential concept in recent reading-related research is the concept of orthographic neighborhood (Coltheart, Davelaar, Jonasson, & Besner, 1977; Landauer & Streeter, 1973). Neighborhoods are necessarily related to the concept of cohorts (Johnson, 1992; Marslen-Wilson, 1984). Both assume that successful lexical access requires the elimination of all similar neighbors—a not unreasonable idea. Unfortunately, both the empirical findings and the theoretical conclusions have been confusing, contradictory, and ambiguous. The operational definition of neighborhood has remained the original definition given by Landauer and Streeter—a mismatch on one letter between the target word and other words of the same length. As also pointed out by Frauenfelder, Baayen, Hellwig, and Schreuder (1993), this measure does not take into account several potentially important factors: (a) the position of the mismatching letters, (b) neighboring words of different lengths, and (c) the similarity of mismatching letters. Given the advantage of accessing words with initial relative to medial or final letters, we should expect position of the mismatching letter to be important. Also, a strong neighbor might be a word differing in word length such as the words *desert* and *dessert*. The definition also cannot be a good index of visual similarity. By definition, *jog* would be a neighbor of *bog* but might not be very confusable because the letters *j* and *b* are not very confusable. On the other hand, we might expect *hay* to be more visually confusable with *bog*, even though the two words have no letters in common. Also, the measure of a mismatch on a single letter becomes almost meaningless for longer words because of the diminishing number of neighbors that differ by just a single letter.

Grainger and his colleagues (Grainger, O'Regan, Jacobs, & Segui, 1989; Grainger & Segui, 1990) find evidence that the presence of one or more higher frequency neighbors impedes word recognition. Andrews (1989) finds evidence that increasing the number of neighbors facilitates word recognition, even when orthographic structure is supposedly controlled (Andrews, 1992). Snodgrass and Mintzer (1993) find either inhibitory and facilitatory effects, depending on the experimental procedure. Paap, Newsome, and Noel (1984) found that word recognition did not depend on the number of orthographically similar neighbors in a test of the hypothesis that words are recognized through their overall word shapes. This same result would also seem to negate any important role for neighborhoods and cohorts in word recognition. Similarly, Johnson (1992) had to assume facilitated processing due to the contribution of sublexical orthographic structure when a larger cohort did not lead to poorer performance.

The major limitation we see with these studies is that investigators have not accounted for other potentially important influences of orthographic structure when evaluating the effects of neighborhood size. To do so, a post hoc analysis of individual item performance is usually necessary. Evaluating the contribution of a source of information is best carried out on performance on individual items. Given individual-item performance, it is possible to assess how much a source of information uniquely contributes to performance. To address the neighborhood issue, we reanalyzed the results of a series of letter recognition experiments. The goal was to use the power of individual items analyses to contrast the concept of neighborhood with other measures of orthographic structure. The results come from a series of experiments by Massaro, Taylor, Venezky, Jastrzembski, and Lucas (1980, chapter 5 and Appendix 5.1). In a series of experiments using a target-search task, subjects were asked to indicate whether a target letter was present in letter strings. In two experiments, the displays were high quality and performance was essentially errorless. An RT measure comes from these experiments. In two experiments, the displays were low quality, and accuracy was the dependent variable. In another experiment, subjects made typicality ratings indicating how much the letter strings looked like English words. Subjects were told to disregard the semantic content of the words and simply to judge them on the basis of spelling. The rating scale went from "least like English" to "most like English" on a scale from 1 to 10.

In these experiments, six-letter words and anagrams of these words were used as test items. The anagrams were selected to give letter strings that represented the four combinations formed by a factorial arrangement of high or low position-sensitive bigram frequency and regular or irregular orthographic structure. There were 40 words and four anagrams of each word for a total of 200 test items. The statistical orthographic measures were summed token position-sensitive single-letter frequency, bigram frequency, and log bigram frequency. The rule-governed orthographic irregularity measures were various sets of rules that were based on phonological and scribal constraints. The results of these studies provided evidence for the use of higher order knowledge in the perceptual processing of letter strings. Lexical status, orthographic regularity, and frequency were found to be important components of the higher order knowledge that is used (Massaro et al., 1980).

Table 1 gives the Pearson correlation coefficients between the three dependent measures and several independent variables. We use Pearson rather than rank-order correlations because the dependent and independent variables are meaningfully interpreted as having interval properties. The independent variables are (a) number of neighbors, (b) log word frequency, (c) position-sensitive summed log bigram frequency, and (d) an irregularity count of the number of orthographic irregularities within the letter string (Massaro et al., 1980, chapter 3). Number of neighbors is defined in the traditional manner: a mismatch on one letter. Although we use log word frequency as an independent variable, we believe that word familiarity is the important psychological variable (Gernsbacher, 1984). The irregularity count gives the number of violations of a set of generative rules of English orthography. All of these variables correlate with performance, but the variables are also highly correlated with one another. Thus, an investigator is not justified in concluding that one of these variables is the critical one, unless the others have been shown to have no independent predictive power. One method to distinguish among the independent variables is to take partial correlations. This method gives the predictive power of a variable when the contribution of other variables has been partialed out.

Table 1
Pearson Product–Moment Correlations Among the Three Dependent and Four Independent Variables

Independent variable	Dependent variable		
	Accuracy	RT	Rating
Number of neighbors	.49	−.23	.43
Log word frequency	.64	−.36	.62
Log bigram frequency	.77	−.64	.83
Irregularity count	.57	−.53	.85

Note. RT = reaction time.

Table 2 gives the Pearson partial correlations between the same three dependent measures and the same four types of independent variables. As can be seen in the table, number of neighbors is not a good predictor of search performance using accuracy or RT as dependent measures, nor is it a good measure of a reader's rating of how much the letter string resembles English spelling. Position-sensitive summed log bigram frequency provides the best predictor of accuracy and RT performance, whereas the irregularity count gives the best description of the ratings. Log word frequency and log bigram also account for independent sources of variance of the rating judgments. Thus, when other structural variables are accounted for, neighborhood size appears to have very little influence on perceptual recognition. These results should warn other investigators that the role of other structural variables must be evaluated

Table 2
Partial Correlations Among the Three Dependent and the Four Independent Variables

Independent variable	Dependent variable		
	Accuracy	RT	Rating
Number of neighbors	.101	.070	.093
Log word frequency	.047	−.063	.585
Log bigram frequency	.483	−.380	.342
Irregularity count	−.040	.102	−.735

Note. RT = reaction time.

before it is safe to conclude that neighborhood size influences reading performance.

Spelling-to-Phonology Regularity

As described in the introduction, another source of information is the relative consistency of the mapping between graphemes and phonemes. We have called this source of information spelling-to-sound regularity (Venezky & Massaro, 1979, 1987). Given a set of spelling-to-sound constraints, the question remains, how can this information be used to scale regularity? Whereas most experimenters have treated regularity as a binary variable, at least one (Rosson, 1985) has tried to create a continuous regularity scale by extracting the log of the weakest (i.e., least common) spelling-to-sound correspondence in a word. This measure, unfortunately, confounds grapheme–phoneme regularity and grapheme frequency of occurrence (Venezky & Massaro, 1987). By this measure, a highly regular but relatively infrequent correspondence (e.g., *qu* → /kw/) would be scaled lower than a common but irregular correspondence (e.g., *ea* → /ɛ/).

A Measure of Grapheme–Phoneme Correspondence

Venezky and Massaro (1987) scaled grapheme–phoneme correspondences using various types or levels of information. Table 3 presents data on the correspondences for the grapheme *c*, derived from an analysis of approximately 20,000 types (Venezky, 1970). The value or fluency score assigned to a particular grapheme–phoneme correspondence is based on the number of occurrences of that correspondence relative to the sum of all correspondences for that same grapheme. That is, for a complete set of correspondences $f_1, f_2, \ldots, f_n$ of a spelling, the fluency score of any f_i is $f_i \times 100$, where multiplication by 100 transforms the distribution from a 0–1 scale to a 0–100 scale. This approach ensures that consistent but infrequent correspondences like *z* → /z/ will have higher fluency scores than inconsistent but frequently occurring correspondences like *ea* → /ɛ/.

A zero-order grapheme–phoneme scaling is based on single letter–phoneme scores without regard for position of letters within words or any higher order contextual or linguistic considerations. This definition leads to treating digraphs such as *th* as sequences of single graphemes rather than as separate units. For the *c* pronunciations shown in Table 3, the zero order fluency scores are /k/ = 74.32, /s/ = 21.98, /š/ = 3.67, and /č/ = 0.03. The total fluency score assigned to a word is assumed to be equal to the mean of its grapheme scores. As an example, the zero fluency score for *chin* would be derived from the separate scores for *c*, *h*, *i*, and *n* at the zero order. In this case, we treat the correspondences of *ch* as c → /č/ and h → /ϕ/.

A first order scaling takes into account multiletter spelling units, so that *chin* is now treated as a sequence of three grapheme units: *ch*, *i*, and *n*. For the second order measure, grapheme positions within the word are taken into account, namely, initial, final, and medial, where medial is everything left after the first (initial) and last (final) graphemes are removed. Third-order scalings admit more general linguistic constraints. Venezky and Massaro (1987) give a more comprehensive discussion of the different orders of scaling. The second-order scaling measure of spelling-to-phonology correspondence will be used in our analysis of multiple influences in naming and lexical decision.

Venezky and Massaro (1987) reanalyzed the results of a series of experiments carried out by Waters and Seidenberg (1985). In their study, word frequency, spelling-to-speech correspondences, and orthographic structure were systematically varied in pronunciation and lexical decision tasks. To increase the power of the post hoc analysis, the results from the six experiments were combined into a single grand analysis. Although we realize that the relative influence of an information source probably differs across different tasks and conditions, we believe the decrease in variability by pooling merits higher priority. This pooled analysis also provides a test of what sources are robust contributions across tasks and conditions. For completeness, we provide separate analyses of the naming and lexical-decision tasks. For each word in a given experiment, the dependent measure for that word was its RT minus the mean RT across all words in that experiment. Every word was used except for those that did not occur in the Kuçera and Francis (1967) word list and were not 4 to 7 letters in length. A total of 505 cases with 218 unique words went into the analysis. Partial correlations, reflecting the correlation of each independent variable with the variance of all other variables pulled out, were carried out on six independent variables.

The results are shown in Table 4. The variables were log word frequency, position-sensitive log bigram and trigram counts, second-order fluency (described in the previous section), an exertion measure of spelling-to-speech, and number of neighbors. Log word frequency, second-order fluency, and position-sensitive log bigram frequency accounted for unique sources of variance of the RTs. Number of neighbors did not correlate with performance, supporting our analysis in the previous section. Faced with a letter string, reading, pronouncing, and making a lexical decision are influenced by the orthographic structure of the letters in the string, the mapping of the letters into speech, and the frequency (or familiarity) of the letter string. These results are compatible with the central assumption of the FLMP

Table 3
The Number of Spelling-to-Sound Correspondences for the Grapheme c Derived From an Analysis of Roughly 20,000 Word Types (After Venezky & Massaro, 1987)

	Word position			
Pronunciation	Initial	Medial	Final	Total
/k/	1,366	718	377	2,431
/s/	150	569	0	719
/š/	0	120	0	120
/č/	1	0	0	1

Table 4
Partial Correlations Between Reaction Time and Six Independent Variables

Independent variable	Partial correlation
Number of neighbors	−.028
Log word frequency	−.293*
Log bigram frequency	−.146*
Fluency	−.137*
Exertion	.026
Log trigram frequency	.082

* $p < .05$.

that multiple sources of information influence reading performance.

Investigators have also hypothesized that the number of higher frequency neighbors of a word is important (Grainger, 1990; Paap & Johansen, 1994). To test this idea, we repeated the partial correlation with this independent variable. We also are aware of one limitation of a partial correlation analysis. If two independent variables are highly correlated with one another, then both variables will tend to have a low partial correlation with the dependent variable even though they are correlated with it. Accordingly, it is important to choose variables for the partial correlation analysis that claim to be independent of one another. With this in mind, we chose four independent variables for a partial correlation analysis: number of higher frequency neighbors, log word frequency, position-sensitive summed log bigram frequency, and second-order fluency. The partial correlations are given in Table 5. As can be seen in the table, all variables but number of higher frequency neighbors produce a significant negative correlation with RT. These results, along with the results in Tables 1–4, support the idea of lexical status, orthographic structure, and spelling-to-speech fluency as important influences in letter and word recognition.

For greater completeness, we include one final set of simple partial correlations to address two additional points. First, as mentioned earlier, there is the question of whether the correlations differ for the naming and lexical decision tasks. Second is the question of whether linear or log word frequency is the more appropriate psychological measure of word familiarity. Paap and Johansen (1994) use a linear measure of word frequency, which then allows a significant influence of the number of higher frequency neighbors. To address these two questions, we reanalyzed the results of the first three experiments of Waters and Seidenberg (1985) that had both naming and lexical decision tasks with the same words. A total of 505 cases with 158 unique words went into this analysis. Partial correlations were carried out on the two dependent measures (naming and lexical decision RTs) for the six independent variables. The independent variables were linear word frequency, log word frequency, position-sensitive log bigram counts, second-order fluency, number of neighbors, and number of higher frequency neighbors.

Table 5
Partial Correlations Between Reaction Time and Four Independent Variables

Independent variable	Partial correlation
Higher frequency neighbors	−.022
Log word frequency	−.230*
Log bigram frequency	−.137*
Second-order fluency	−.193*

* $p < .05$.

Table 6 gives the simple and partial correlations and significance levels. As can be seen in the upper left corner of the table, the two tasks correlated with one another. Overall, naming and lexical decision give similar results except for the bigram and fluency measures. The influence of bigram frequency is somewhat larger in lexical decision than in naming, whereas the reverse holds for fluency. The results also show that log word frequency is the more meaningful measure of word familiarity. Contrary to any known process, linear word frequency has a significant positive partial correlation with RT. Log word frequency, on the other hand, gave the expected account of RT. Neither number of neighbors nor number of higher frequency neighbors accounted for any unique variance. When other influences are accounted for, these analyses are generally consistent with the previous ones and confirm our skepticism of a psychological role for neighbors.

Related Research and Cross-Linguistic Comparisons

The framework given by the FLMP is also consistent with some recent results reported by Coltheart and Rastle (1994). They found evidence for both lexical and sublexical influences in a lexical decision task. RTs were longer to words that violated spelling-to-speech regularity at the beginning of the word relative to violations toward the end of the word. This result illustrates that letter information mediates word recognition and that letters are mapped into speech or lexical representations in a roughly left-to-right sequence. Within the context of the FLMP, sublexical information early in the word has more influence than sublexical information later in the word. Consistent information from spelling to phonology will necessarily speed up the pronunciation or lexical decision, because there are two consistent sources of information supporting the alternative. Inconsistent information will slow down the pronunciation or lexical decision, because the inconsistent source of sublexical information will be integrated with the lexical support and decrease the support for the correct alternative. The sooner the inconsistent information is processed, the more it will lengthen lexical decision time.

It should be stressed that the partial correlations do not necessarily support the FLMP over other models. The main goal of these analyses was to test the assumption that multiple sources of information influence perceptual identification, lexical decision, and naming. Obviously, we have a plethora of models, and only fine-grained experimental procedures specifically aimed at testing between models have a chance of being successful in reducing the number of viable models.

Table 6
Simple and Partial Correlations Between Pronunciation and Lexical Decision Reaction Time and Six Independent Variables

	Simple								Partial	
V	PR	LD	WF	LW	LB	F2	NH	NN	PR	LD
PR										
r	—	.601	.079	−.250	−.263	−.290	−.006	−.236	NA	NA
p	NA	<.001	.323	.002	<.001	<.001	.936	.003	NA	NA
LD										
r	.601	—	−.160	−.488	−.423	−.257	.243	−.094	NA	NA
p	<.001	NA	.044	<.001	.001	.001	.002	.241	NA	NA
WF										
r	.079	−.160	—	.666	.316	−.045	−.275	−.057	.342	.271
p	.323	.044	NA	<.001	<.001	.571	<.001	.479	<.001	<.001
LW										
r	−.250	−.488	.666	—	.297	.098	−.560	−.022	−.291	−.291
p	<.002	<.001	<.001	NA	<.001	.222	<.001	.788	<.001	<.001
LB										
r	−.264	−.423	.316	.296	—	.299	.182	.328	−.154	−.363
p	<.001	<.001	<.001	<.001	NA	<.001	.022	<.001	.057	<.001
F2										
r	−.290	−.257	−.045	.098	.299	—	.100	.185	−.156	−.111
p	<.001	.001	.571	.222	<.001	NA	.209	.020	.054	.172
NH										
r	−.006	.243	−.275	−.560	.182	.100	—	.667	−.042	.112
p	.936	.002	<.001	.001	.022	.209	NA	<.001	.607	.168
NN										
r	−.236	−.094	−.057	−.022	.328	.185	.667	—	−.062	−.056
p	.003	.241	.479	.788	<.001	.020	<.001	NA	.446	.490

Note. V = variable; PR = pronunciation; LD = lexical decision; WF = word frequency; LW = log word frequency; LB = position-sensitive summed log bigram frequency; F2 = second-order fluency; NH = number of higher frequency neighbors; NN = number of neighbors; NA = not applicable.

Paap and Noel (1991) found that low-frequency exception words are processed more quickly with increases in memory load. In terms of the FLMP, the memory load evidently interferes somewhat with the assembled sources of information, allowing the addressed source to have a stronger influence on performance. This explanation is similar to that given by the dual-route model, revealing that it will not be easy to distinguish between the two models.

Grainger and Jacobs (1994) have proposed a dual readout model of the WSE. This idea is related to the Paap, Newsome, McDonald, and Schraneveldt (1982) model in which readers can respond with information from one of three levels: the letter, the syllable, or the word. These models are important because they acknowledge the lack of correspondence between the subject's response and some particular perceptual experience. That is, when subjects are asked to report a letter at a particular position, we cannot simply assume that the subject reported solely on the basis of the representation of the letter at that position. This assumption of readout at the letter level was central to the IAM. It is now well-known that perceivers are influenced by multiple sources of information from multiple levels, and they find it impossible to use information selectively from only one level. These observations reveal two major barriers to predicting the WSE. The first is that we do not know which levels of experience are responsible for the report: sensory, perceptual, orthographic, semantic, and so on. The second is that subjects are free to report their decision at a range of times during or after the test stimulus. What is reported and when it is reported are probably influenced by a plethora of experimental manipulations and individual strategies—reducing the predictive power of theoreticians. Not surprisingly, psychology does not play second fiddle to the chaos of physics. We have our own uncertainty in great abundance.

We should not forget that the influence of context on pattern recognition is not limited to written language. Lines can be better recognized in a coherent context than in a meaningless context or even presented alone (Weisstein & Harris, 1974; Williams & Weisstein, 1978). Meaningful objects such as chairs and faces are more easily recognized than their scrambled counterparts (Davidoff & Donnelly, 1990; Tanaka & Farah, 1993). Phonological and lexical context can influence recognition of a speech segment (Ganong, 1980; Massaro, 1989; Massaro & Cohen, 1991). It is also the case that object recognition is facilitated in a coherent scene relative to a random mixture of objects in the scene (Biederman, 1972). Finally, it is now well-known that skilled chess players more easily perceive and remember meaningful board positions than a random placement of the pieces (Chase & Simon, 1973). Written language, then, is just one of many situations in which context and stimulus information are exploited in pattern recognition.

Reading researchers are converging on the reasonable idea that all languages are processed similarly, with the differences between languages being one of degree rather than kind. Within the framework offered by Massaro (1992), the differences found between languages are due to differences in information and not to differences in information processing. The outcomes of feature evaluation represent how informative each source of information is. The integration and decision algorithms specify how this information is processed. This distinction plays an important role in locating several sources of variability in our inquiry. Variability in information is analogous to the variability in predicting the weather. There are just too many previous contributions and influences to allow quantitative prediction of the information available from a given source for a given subject. In addition, small early influences can lead to dramatic consequences at a later time (the butterfly effect in chaos theory). However, once this variability is accounted for (e.g., by estimating free parameters in the fit of the model), we are able to provide a convincing description of how the information is processed and mapped into a response. Although we cannot predict a priori how informative a source will be, we predict how the two sources of information are integrated. In addition, the model does take a stand on the evaluation process in the sense that it is assumed that the sources of information are evaluated independently of one another and that there is continuous information from each source.

Within this framework, we expect cross-linguistic differences in information but not in information processing. Languages can be distinguished in terms of orthographic depth. Recall that a shallow orthography has a relatively direct mapping of spelling-to-phonology, whereas a deep orthography has a less direct mapping. Investigators have also distinguished between "assembled" and "addressed" routes to reading. The assembled route involves the blending of sublexical spelling-to-speech patterns to achieve lexical access. The addressed route involves a direct mapping of the orthographic form of the word and its meaning. It might be (and has been argued) that readers of shallow orthographies use the assembled route, whereas readers of deep orthographies use the addressed route. Within our framework, we believe that readers can use both routes as sources of information that are integrated to achieve meaning.

We find recent results and conclusions consistent with our view. Besner and Smith (1992), for example, provide strong evidence that even shallow orthographies are not limited to the assembled route to the lexicon. Both word frequency and priming effects were found with unfamiliar words created by the transcription of kanji into katakana or from katakana into hiragana. The authors conclude that "even in a shallow orthography the orthographic input lexicon is directly activated by print at least some of the time, and that this process contributes to reading in shallow orthographies" (p. 60). Our reformulation of this principle is simply that there is always some activation of the orthographic input lexicon, but that this activation may be small relative to the activation generated along the assembled route. Similarly, Carello, Turvey, and Lukatela (1992) believe that "the basic mechanism of written language processing is the same for all languages" (p. 211). These researchers are now taking care to clarify that finding a positive influence of one process does not contravene a contribution of another. That is, finding an effect of assembled phonology does not imply that addressed phonology is not functional, nor does an effect of addressed phonology imply that assembled phonology is not functional. In all cases, the most informative sources of information will have the greatest impact on performance. Carello et al. (1992) observe that there is a greater invariance in most languages between orthography and phonology compared to the relationship between orthography and meaning or syntax. In terms of percept–act compatibility (Massaro, 1990), the written form of a word in both shallow and deep orthographies is usually highly compatible with its pronunciation.

Van Orden et al. (1992) also demonstrate involvement of assembled phonology in several reading tasks. They blame the symbolic human-information processing metaphor for "eroding phonology's role in theories of printed word identification" (p. 281). This seems a bit far-fetched. Our conclusions in the phonological mediation debate (Massaro, 1975b) were always of the form that phonology was not necessary for word recognition, but at that time the perspective that multiple sources of information influenced performance was lacking. With this new perspective, it is instructive to study how these sources together influence performance. Further demonstrations of a main effect of one source are probably unnecessary.

Seidenberg (1992) concludes that the meaning of a word is "built up on the basis of activation from multiple sources" (p. 113). Consistent with this hypothesis, Massaro, Weldon, and Kitzis (1991) demonstrated that word retrieval was influenced by both letter information and semantic associates. The combination of these two sources of information followed the integration algorithm predicted by the FLMP. Some of the best evidence for multiple sources in word recognition is Venezky and Massaro's (1987) reanalysis of the Waters and Seidenberg (1985) results (see the section titled Multiple Influences in Reading Tasks). Perfetti, Zhang, and Berent (1992) find both phonemic and graphemic contributions to word identification using a novel backward masking task. The mask shares either phonemic or graphemic information with the test, and performance is facilitated given each of these sources of information.

Hung, Tzeng, and Tzeng (1992) describe how a phonological source of information is even available in the logographic writing system of Chinese. This information is not unambiguous, but we now know that perceivers exploit even relatively ambiguous sources of information. Supporting the theme of multiple sources of information, Hung et al. show how both written and phonological sources of information contribute to reading Chinese characters.

Summary and Conclusion

Our research on reading has followed two somewhat independent but related streams. On the one hand, we have provided a fine-grained experimental and theoretical analysis of the psychological processes involved in reading letters and words. Experimental situations have been devised to test among current models of reading. An important distinction throughout this work is the difference between independence and nonindependence explanations of the interaction of context and sensory processing (Massaro, 1978, 1979). Independence models assume that sensory processing at the letter level is not influenced by context. Nonindependence theories take on a variety of forms, but all of them assume that sensory processing at the letter level is influenced by context. Various investigators have assumed that (a) context influences feature extraction, (b) higher order units intervene and modify sensory processing of the letters, (c) hypotheses intervene to direct the sensory feature processing, or (d) memory representations are activated that modify the processing and representation of the component letters. The IAM qualifies as an nonindependence model because top-down connections from the word level to the letter level in memory cause context to modify the sensory processing and representation at the letter level. Our experimental and theoretical work has falsified this central assumption of the IAM (Massaro, 1979; Massaro & Cohen, 1991).

The FLMP, an independence model, provides a good quantitative description of the joint contributions of letter information and context in reading. The WSE is necessarily modulated by lateral masking and processing time. A word has the advantage of orthographic context and the disadvantage of lateral masking. A letter presented alone has the advantage of no lateral masking, but it does not have the additional source of information provided by reliable orthographic context. A nonword or a letter surrounded by dollar signs has the disadvantage of both lateral masking and no orthographic context. In addition, the FLMP accurately describes how letter information and context are processed in real time to determine performance. The dynamics of information processing along with the joint influence of several sources of information are nicely described by the FLMP.

The second branch of our research involves uncovering and describing the multiple influences that contribute to reading. Documenting a positive contribution of a source of information is best carried out on the analysis of performance on individual test items. Given individual-item performance, it is possible to assess how much each source of information uniquely contributes to performance. Our early research documented both statistical and rule-based contributions to the recognition of letters in words, pseudowords, and nonwords. More recently, we have extended this approach to the reading of words in naming and lexical decision tasks. Results indicate that word frequency, sublexical frequency, and spelling-to-speech correspondences jointly contribute to performance (Venezky & Massaro, 1987). In both the letter recognition studies and the word reading experiments, no unique contribution was found for number of neighbors.

Finally, our findings and theoretical framework take a strong stance on the two routes to reading. Traditionally, investigators have distinguished two separate routes for reading a written letter string. Reading can occur by either a direct mapping from the letter information to the word or an indirect mapping from the letter string to a speech code that accesses the word. This dual-route model has been envisioned as a horse race in which the fastest route to the word completely determines lexical access. This view assumes that only the horse that crossed the finish line first has any influence. In our view, however, the orthographic information and the spelling-to-speech information contribute in parallel to lexical access. From our grandstand view of the race, both horses are simultaneously contributing to the outcome. Furthermore, although we use the horse-race metaphor, we doubt that lexical access is a discrete process that can be characterized by a horse crossing a finish line. Instead, lexical access should be viewed as analogous to our findings on letter recognition. Information about a letter accumulates continuously over time and comes from multiple sources. Similarly, lexical information must occur gradually and is influenced by several sources. There is no discrete finish line and both horses are simultaneously contributing to the outcome.

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