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The Magic of Reading: Too Many Influences for Quick and Easy Explanations

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A skilled reader cannot help but read even the blandest banners on the information highway and real highways. Like listening, contact with the linguistic signal is all that seems to be necessary. This behavior is easily exposed by the Stroop color word test. You are asked to name the color of the print of each of the words in a list. When the words are the names of other colors (e.g., the word *blue* printed in red), however, you either switch gears into slow motion or name the written words rather than the colors (i.e., in our example, you incorrectly answer "blue" rather than "red"). The written word overrides your intention to name the color, contributing to the impression that reading is clearly magical.

The goal of this chapter is to show that reading of words, though indeed magical, is a magic that has been well examined and basically involves the ability of the reader to exploit multiple sources of information in a (overlapping) series of information-processing stages. Many of these sources and stages were studied by Dick Venezky, which makes this chapter a tribute to his insights into the magic of reading. Our proposal is grounded in the assumption that reading words is fundamentally a pattern recognition process, which involves imputing meaning to an input pattern. As our guide to the understanding of visual word recognition, we use a pattern-recognition model, the fuzzy logical model of perception (FLMP), that has achieved scientific success in reading as well as in several other domains of information processing.

The general assumption of the FLMP is that well-learned patterns, such as written words, are recognized by applying a general algorithm, regardless of the modality or the nature of the pattern (see, e.g., Massaro, 1998). The FLMP assumes three operations: feature evaluation, feature integration, and decision. All three processes are successive but overlapping. Feature evaluation provides the degree to which each feature of the stimulus matches the corresponding feature in each prototype in memory. Prototypes are summary descriptions and contain a conjunction of various ideal properties (features) that a member of this prototype category should have. Fuzzy truth values (Zadeh, 1965) reflect the degree to which a given stimulus matches to the features of a prototype. The fuzzy truth values lie between *completely false* (0) and *completely true* (1). In addition to the multiple bottom-up sources of information, various top-down sources are assumed. These sources in reading are the orthographic, phonological, syntactic, semantic, and pragmatic structure, as well as the sublexical mappings from print to sound. Continuous information is available from each source, and the output of the evaluation of each source is independent of the output of another source (see Fig. 3.1).

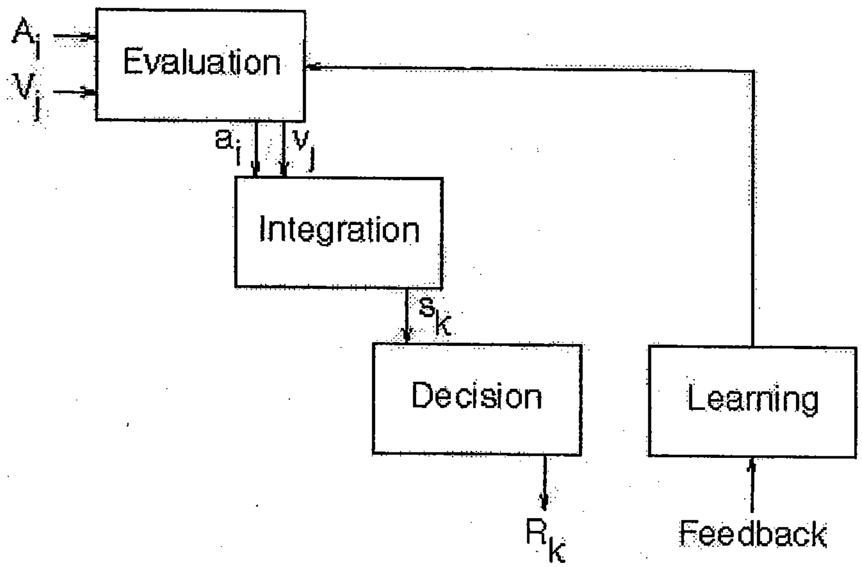

FIG. 3.1. Schematic representation of the FLMP to include learning with feedback. The three recognition processes are shown to proceed left to right in time to illustrate their necessarily successive but overlapping processing. These processes make use of prototypes stored in long-term memory. The sources of information are represented by uppercase letters. Auditory information is represented by A_i and visual information by V_j. The evaluation process transforms these sources of information into psychological values (indicated by lowercase letters a_i and v_j). These sources are then integrated to give an overall degree of support, s_k, for each alternative k. The decision operation maps the outputs of integration into some response alternative, R_k. The response can take the form of a discrete decision or a rating of the degree to which the alternative is likely. The feedback is assumed to tune the prototypical values of the features used by the evaluation process.

Feature integration combines all degrees of matches from each source of information for each prototype. The outcome of this process is the total degree to which each prototype matches the stimulus. The third process in the model makes a decision based on a relative goodness rule (Massaro & Friedman, 1990), the relative support of one alternative compared to the support for all other alternatives. The model predicts that one feature has its greatest effect when a second feature is the most ambiguous. Through this assumption, the model predicts that the time for decision increases with the ambiguity of the information available to the decision stage (Massaro, 1987).

Consider the elaboration of the FLMP, depicted in Fig. 3.2, as a description of how the many different sources of information can influence letter and word processing in reading. The presentation of a letter pattern initiates a sequence of processing stages. Visual features are evaluated, and this information has several consequences. First, complete or even partial information from the features can activate letter patterns in long-term memory. Needless to say, the more visual information available, the more easily letter and word recognition can take place. Second, recognition of letters can be supplemented by the reader's knowledge of how letter patterns occur in the language. We call the form of this knowledge ortho-

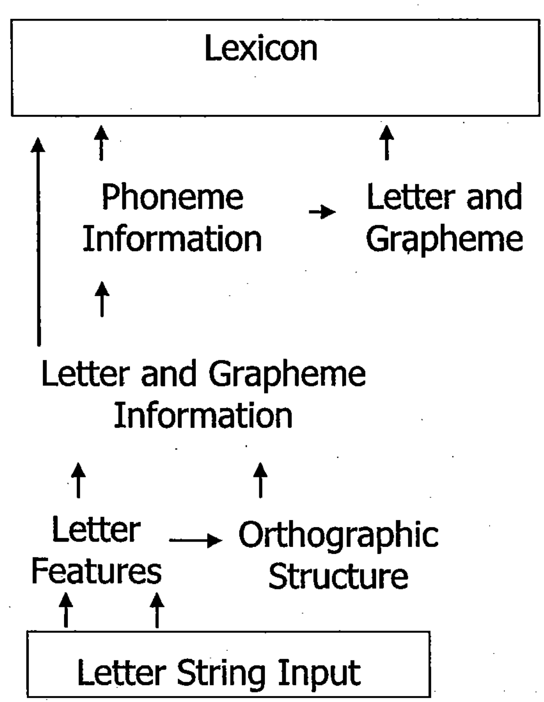

FIG. 3.2. The different processes between presentation of a letter string and access to the lexicon as described by an elaboration of the fuzzy logical model of perception, which shows the processing streams of the many different sources of information that can influence letter and word processing in reading.

graphic structure. Letters that occur together more often should be easier to recognize than those in an infrequent or unlawful arrangement because of the contribution orthographic structure.

Letter information activates words and spoken language representations, which we call phoneme information. Because readers also know the relationship between sounds and spellings, the activation of phonemes in turn activates a set of spelling patterns. Like the information about the association of letters to phonemes, the activated spelling patterns associated with phoneme information also feed forward to the lexical level and can aid or hinder word activation. A phoneme pattern limited in the number of ways it can be spelled would facilitate lexical access because only these spellings would activate the lexicon. When a phoneme pattern can be spelled in many different ways, it would hinder lexical access because a larger set of different possible spellings would be activating the lexicon. The information passed from this sound-to-spelling source (sound-to-spelling fluency) does not affect evaluation or integration but can influence the time needed for decision making (Massaro, 1987).

Using this model as a framework, we discuss three of the sources potentially involved in the word recognition process in detail. The first source is visual influences, such as the features of letters and the overall shape of a word. Second, we describe research indicating that knowledge about the orthographic structure of a word might help its recognition. Finally, we discuss evidence that the two-way association between orthographic and phonological information influences the word recognition process.

INFLUENCES IN WRITTEN WORD RECOGNITION

In our model, letters and words are recognized via the visual features that make them up. Features can be elemental or relatively global depending on how much of a letter they describe. Elemental features of uppercase *E* include three horizontal lines and one vertical. A global feature of lowercase *c, e,* and *o* is a circular envelope that distinguishes them from other letters, such as *f, h,* or *j*. Discovering the functional features in reading is a challenging empirical endeavor (for reviews, see also Massaro & Sanocki, 1993). Our goal here is simply to provide the reader with the flavor of what is already known and recent studies addressing this problem.

Reading research began as an active area of psychological inquiry at the turn of the century (see Huey, 1968; Woodworth, 1938). For the last three decades, after a period of relative inactivity during the heyday of behaviorism, the process of reading written words has been intensely studied. One finding that led to this renewed interest was the demonstration that a letter could be better recognized when presented in the context of a word than when presented in a random letter string or even when presented alone. This advantage, called the word advantage or word superiority effect, was shown to exist even if the possibilities of postperceptual guessing and memory loss were eliminated (Reicher, 1969).

What was it about words that contributed to this word advantage? A natural interpretation of the word superiority effect is that words are recognized as wholes without intermediate processing of the features of letters that make them up. This little paragraph has circulated cyberspace in the last quarter of 2003, with the implication that words are read as wholes:

> Aoccdrnig to a rscheeahcr at an Elingsh uinervtisy, it deosn't mttaer in waht oredr the ltteers in a wrod are, the olny iprmoetnt tihng is taht the frist and lsat ltteer are in the rghit pclae. The rset can be a toatl mses and you can sitll raed it wouthit porbelm. Tihs is bcuseae we do not raed ervey lteter by itslef but the wrod as a wlohe.

Are you impressed that you were able to read this passage? Maybe you shouldn't be because you read much more slowly and laboriously than normal. Reading aloud would have also revealed the added difficulty created by scrambling the internal letters. Holistic word recognition is an old idea in reading research. Like John Updike, we are not fans of holism: "Next to the indeterminacy principle, I have learned in recent years to loathe most the term 'holistic,' a meaningless signifier empowering the muddle of all the useful distinctions human thought has labored at for two thousand years" (Roger Lambert, in John Updike's *Roger's Version*, p. 171).

Some researchers and educators (Haber, Haber, & Furlin, 1983; Johnson, 1975) proposed that words are recognized as patterns of unique shapes rather than as unique sequences of letters. We call these properties global supraletter features because they supposedly are composed of multiletter patterns and even whole word patterns. The earlier paragraph shows convincingly that we can read scrambled words, even if they are misspelled or incomplete (like *rscheeahcr* or *iprmoetnt*). But are we actually reading words as a whole? And do we need the first and last letter to stay in their original position?

A little thought reveals that global features cannot be sufficient for even the expert reader. One of the strongest arguments against the idea of supraletter features is the small potential contribution of supraletter features to reading. Overall word shape, for example, does not sufficiently differentiate among the words of a language. In a classic study, Groff (1975) examined the shapes of high-frequency words taken from schoolbooks. The shape was defined by drawing a contour around the letters.

Only 20% of the 283 words was represented by a unique shape. Groff rightly concludes that the small number of words that can be represented by a unique shape precludes the use of this cue for accurate word recognition. Using a much larger sample of words, Paap, Newsome, and Noel (1984) also showed that there is not sufficient uniqueness of word shapes that could be used to mediate word recognition.

There is also experimental evidence against the idea of word recognition based on supraletter features. Adams (1979) asked whether disrupting word shape (mixing upper- and lowercase and type fonts of letters) eliminates the identification advantage of words over nonword letter strings. If the word shape is contributing to the word advantage, because it is used to access the lexicon, then the advantage should diminish when the shape of words is altered and can therefore no longer be used to access the mental lexicon. The word advantage did not change when the global word shape was eliminated (see also Thompson & Massaro, 1973).

One would think that the word shape idea was sufficiently demolished but Paap and his colleagues (1984) tested whether the number of words that share a certain word shape could still influence word recognition. When a shape matches a small set of words (e.g., *cellar*), then the shape feature restricts the lexical search to this small set of candidates, and therefore all words of this small set should be processed faster or more accurately than words in a larger set (e.g., *recall*). When the shape is shared by a large set of words, a response cannot be given until letter identification is almost completed. Contrary to this expectation, Paap et al. (1984) actually found that words with rare shapes are not accessed faster than words with common shapes, falsifying the word shape hypothesis.

Although three decades of empirical evidence indicate that words are not read as a whole, the first and last letters may be more important than the medial ones. The paragraph of scrambled words that was sent so actively over the Internet could have been inspired by the research of Jordan and colleagues (Jordan, Thomas, Patching, & Scott-Brown, 2003). Jordan et al.'s study goal was to show that exterior letters (i.e., the first and the last letter of a word) are special in reading. Indeed, there is some truth to the hypothesis that first and last letters have an advantage over their embedded letter cohort. This advantage occurs because neighboring letters are not always kind to one another. Lateral masking refers to the interference that a letter has on its neighbor(s). An embedded letter in a word has two interfering neighbors, whereas the first and last letters have only one. Accordingly, a letter will necessarily be (ceteris paribus) more visible at the first and last position than in the middle of a word. Jordan et al.'s results could be simply evidence of this lateral masking rather than implication of a special functional unit of exterior letters used to access the mental lexicon.

If the first and last letters were responsible for word recognition, then we would also expect that words would be uniquely defined by their first and last letters in analogous fashion to what we expected from word shape. A quick look at the 1,000 most frequent words in English reveals that there are many words that share their first and last letters, even when word length is controlled:

wish wash	*while whole*	*that test*
short shoot	*whose where*	*step stop*
share shape	*week weak*	*shake share*
wide wife	*tree true*	*scale scene*

In the spirit of finding a magical solution, we thought that it would be valuable to combine the whole word shape and first-last letters solutions and determine if these two factors in combination provide sufficient information for reading words. We found that only 9% of the 1,000 most frequent words was uniquely defined by their exterior letters. Adding word length as a defining feature increased this percentage to 40%. In comparison, only 24% of the words has a unique word shape. When exterior letters, interior word shape, and length were considered as features, 75% of the thousand most frequent words was uniquely described. At first glance, the reader might believe that three out of four times is not bad. However, this requires the reader to recognize the first and last letters, the length of the word, and the word shape of the interior letters. This is not a trivial amount of processing to bypass a strategy simply of processing the letters of the word.

Although we have rejected minimalist hypotheses about reading words, we have not yet accounted for the magic of word recognition. What is it about words that make them so easy to recognize by the expert reader? To better appreciate how words are read, it is important to understand that readers can operate reasonably well with partial information but sometimes must falter. This is a common outcome in pattern recognition more generally. We recognize our friend in a crowd and then discover it was not our friend. Another friend who shaved his beard goes unnoticed. All of us have experienced misunderstanding a sentence because we recognized a word incorrectly. This shows that we do not usually require complete unambiguous information before making a decision in word recognition. Second, we use multiple sources of information in pattern recognition. Many sources of nonvisual information supplement the featural information from the letters. In our infamous paragraph, syntactic and semantic constraints facilitated its reading. A colleague's skilled fourth grade reader had trouble with the paragraph, ostensibly because she had less knowledge that was critical to reading its visually degenerate form. Another important source of information is knowledge about the orthographic structure of the language (Massaro, 1975; Venezky & Massaro, 1987).

ORTHOGRAPHIC STRUCTURE INFLUENCES IN WRITTEN WORD RECOGNITION

Orthographic structure refers to the fact that a written language, such as English, follows certain rules of spelling. These rules prohibit certain letter combinations and make some letters and combinations much more likely in certain positions of words than others. There is evidence that readers use these constraints in the written language in word recognition. Venezky's (1970) seminal analysis of English orthography offered this perspective as an alternative account of the word superiority effect. He found that there was a considerable amount of sublexical structure in English that could be used in reading and spelling. His early empirical studies carried out with Calfee and colleagues (e.g., Calfee, Chapman, & Venezky, 1972) tracked the growth of this understanding across the development of reading skill. Isolating these sublexical influences on word recognition is, however, not easy. There are methodological and technical challenges that impede progress, as well as theoretical controversies that continue unabated.

An important question is the nature of a reader's knowledge about orthographic structure. It is possible to distinguish between two broad categories of orthographic structures: statistical redundancy and rule-governed regularity (Massaro, Taylor, Venezky, Jastrzembski, & Lucas, 1980; Venezky & Massaro, 1979, 1987). The first category includes all descriptions derived solely from the frequency of letters and letter sequences in written texts. The second category includes all descriptions derived from the phonological constraints in English and scribal conventions for writing words as sequences of letters. Although these two descriptions are highly correlated in written English, it is possible to create letter strings that allow the descriptions to be orthogonally varied. Our collaborative studies indicated some psychological reality for both frequency and the regularity description of orthographic structure. The results of these studies provided evidence for the use of top-down knowledge in the perceptual processing of letter strings. Lexical status, orthographic regularity, and frequency appear to be important components of the higher order knowledge that is used (Massaro et al., 1980). In addition, an item analysis of Waters and Seidenberg's study (1985) found that word frequency, spelling-to-sound correspondences, and orthographic regularity influence the time needed to identify and name a word as well as the accuracy of this recognition performance (Massaro & Cohen, 1994; Venezky & Massaro, 1987).

SPELLING-TO-SOUND INFLUENCES IN WRITTEN WORD RECOGNITION

Returning to the reading model shown in Fig. 3.2, it can be seen that letter patterns can be mapped into spoken language, and this information can be used to recognize printed words. The best-known models built on Venezky's seminal book in 1970, which based on his dissertation gave the first systematic analysis of the correspondence between orthography and phonology in English. Dual-route models (Coltheart, 1978; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Forster & Chambers, 1973) assumed a mostly rule-based mapping of the letter string into its pronunciation. Pronunciations for regular words like *hint* and nonwords can be assembled using grapheme-phoneme correspondence rules. This process will succeed for regular words but not irregular words, such as *pint*, because an incorrect phonological code will be assembled. Correct pronunciations for irregular words must therefore be retrieved along a second route directly by accessing the lexicon.

Evidence supporting the dual-route assumption was that regular words were named more quickly than exception words (Baron & Strawson, 1976; Gough & Cosky, 1977; Stanovich & Bauer, 1978). The dual-route model and its implementation predict this result (Coltheart et al., 2001). The model assumes that for irregular items the information sent from the lexical and from the nonlexical route to the phoneme system will conflict. The size of the effect is determined by the difference in speed of the lexical route in comparison to the nonlexical route. This predicts an interaction between regularity and frequency. For high-frequency irregular words, phonological information from the lexicon is available sooner than for low-frequency words and therefore has less of a chance to be inhibited by information from the grapheme-phoneme correspondence route. This mechanism, in addition to the assumption of serial left-to-right processing, also predicts a serial position effect of regularity (Rastle & Coltheart, 1999; but see Rastle & Coltheart, 2000; Zorzi, 2000).

Our model differs from the dual-route model in that there are many parallel influences in word recognition, not separate routes. We also prefer the descriptor *streams* to describe the continuous and temporal overlapping nature of these influences. As with other sources of information, an empirical challenge is to determine to what extent sound-to-spelling information influences word recognition. In addition, it is important to understand how this influence occurs in the processing leading up to word recognition. We now present two different views about how sound-to-spelling information influences word recognition.

Lexical Consistency

Contrary to the idea that sublexical spelling patterns can be mapped to sound, Glushko (1979) proposed a new concept of lexical consistency. Glushko defined in his activation and synthesis model words that only activate similarly pronounced words as consistent and if they activate words with other pronunciations as inconsistent. One important difference between spelling-to-sound regularity and lexical consistency is that words are not consistent or inconsistent based on their own spelling but only in relation to other words that are activated while processing them. Given these descriptions of regularity and consistency, words can be irregular and inconsistent, irregular and consistent, regular and consistent, or regular and inconsistent.

If consistency is psychologically meaningful, then consistent regular words (e.g., _EEK as in WEEK, which shares the pronunciation with all other words including _EEK, i.e., CHEEK, CREEK, MEEK, REEK, SEEK, and SLEEK) should be named more quickly than regular inconsistent words (e.g., _ORK as in CORK, which shares the pronunciation of _ORK with FORK and PORK, but not with _ORK in WORK). Results from Glushko (1979) and others (e.g., Andrews, 1982; Jared, 2002; Seidenberg, Waters, Barnes, & Tanenhaus, 1984) support this prediction, which indicates that consistency is a meaningful concept and that regularity cannot fully account for the mapping between orthography and phonology during word recognition because it does not predict a difference between inconsistent-regular and consistent-regular words.

The evidence for the lexical consistency account was thought to falsify models that incorporated a rule-governed conversion from spelling to sound. However, this is not necessarily the case. For example, the dual-route model (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart et al., 2001) traditionally assumed only a rule-based mapping from spelling to sound. However, Coltheart and colleagues (Coltheart et al., 2001) show that their dual-route model can simulate spelling-to-sound consistency effects. Therefore, the consistency effect no longer falsifies the dual-route model. This new assumption morphs their model into one that is much more similar to the FLMP depicted in Fig. 3.2.

Spelling-to-Sound Fluency

We offered an alternative to the lexical consistency description by formalizing a fluency metric that was meant to capture systematic occurrences that exist between spelling and sound in the input language (Venezky &

Massaro, 1987). A written letter string would have high fluency to the extent that its spelling patterns mapped in a consistent way to spoken language. Low fluency would correspond to a case in which the sublexical spelling patterns of a word are not very predictive of its pronunciation.

We also assumed that a critical variable for the spelling-to-sound fluency was the frequency of occurrence of the spelling-to-sound associations. Frequency of exposure is an important influence on behavior. Infants, for example, can be attuned to systematic occurrence of speech segments by a very short exposure (Saffran, Newport, & Aslin, 1996). According to the sublexical fluency approach, the correspondences of the sublexical units, not just the correspondence of the word, are functional. Zero-order fluency is a simple measure of single letters and their pronunciation. The letters of the word THIN would be mapped in the following way: T to /θ/, H to a blank, I to /ɪ/, and N to /n/. First-order fluency allows the input spelling to be partitioned into multiletter spelling units (e.g., CHIN is treated as a sequence of three grapheme units, CH, I, and N). Second-order fluency measure acknowledges that the positions of the graphemes would be informative (e.g., the CH in CHIN would have a different fluency measure than the CH in ACHE). Venezky and Massaro (1987) found that second-order fluency independently predicted 14% of the variance in both naming and lexical decision tasks, after other sources of variance (e.g., word frequency) were partialed out.

We now turn to another potential influence in word recognition, which concerns how sound maps into spelling.

SOUND-TO-SPELLING INFLUENCES IN WRITTEN WORD RECOGNITION

Lately, researchers have tried to show that a critical variable is not only how letter patterns map into spoken language but also how spoken language maps back into written language. Stone, Vanhoy, and Van Orden (1997) operationalized this idea in terms of the concept of feedback (sound-to-spelling) consistency. This two-way street of word recognition was inspired by interactive activation. The principle of interactive activation assumes that the activation is transmitted back and forth between different layers of neural units. In contrast, noninteractive models, such as our FLMP (Massaro & Cohen, 1994), suggest a strict feedforward flow of information.

Stone et al. (1997) used a lexical consistency framework to analyze whether a spoken language segment can be spelled in more than one way. For example, the segment /_ip/ can be spelled either _EAP as in HEAP or _EEP as in DEEP. Therefore, a word with this segment is sound-to-spelling inconsistent. In contrast, the segment /_ob/ could only be spelled as _OBE, as in the words PROBE and GLOBE, which are therefore called sound-to-spelling consistent words. Using this measure, Stone et al. not only replicated the spelling-to-sound consistency effect but also showed that sound-to-spelling consistency played a role in the lexical decision. Ziegler, Montant, and Jacobs (1997) replicated Stone et al.'s results successfully with French monosyllabic words in the lexical decision task.

Methodological Issues

Peereman and colleagues (Peereman, Content, & Bonin, 1998) argued that Ziegler et al.'s (1997) results were due to a confound of subjective familiarity. The subjective familiarity measure is based on a rating of how familiar a typical reader is with a word. Peereman et al. found that when subjective familiarity is entered as a covariate in Ziegler et al.'s study, no significant sound-to-spelling consistency effect is found. Peereman et al. were also not able to replicate sound-to-spelling consistency effects in the naming task or in the lexical decision task for French words when subjective frequency in print, as estimated by independent ratings, was controlled.

Not surprisingly, however, the Peereman et al. (1998) study can be criticized on several counts. Importantly, they did not control for the second phonemes in their test words. There were more consonant cluster onsets in the sound-to-spelling inconsistent condition than in the sound-to-spelling consistent condition. Peereman et al. found no significant sound-to-spelling consistency effect, but if consonant-cluster onsets decrease reaction time, then this effect could have cancelled out the sound-to-spelling consistency effect (see also Kessler, Treiman, & Mullennix, 2002). Given these ambiguous findings, we decided to explore further the existence and generality of the sound-to-spelling consistency effect.

A Systematic Investigation of the Sound-to-Spelling Consistency Effect

The first two studies attempted to replicate both the spelling-to-sound and sound-to-spelling effect in a 2 × 2 factorial design in naming aloud while circumventing methodological problems of previous studies (Peereman et al., 1998; Ziegler et al., 1997). To avoid potential problems using a voice key, we recorded participants' responses and analyzed them with offline visualization methods to determine the onset of the articulation in the sound wave. To be able to record a more direct measure of articulation with the use of offline visualization procedures, we used a postvocalic naming task (Kawamoto et al., 1998). In this task, the participant was cued before each test trial and was asked to initiate and to produce continuously an "uhhhh" sound when the stimulus is presented. In this postvocalic naming task, the participant must stop production of the vowel sound before the test word can be named aloud (Kawamoto, Kello, Jones, & Bame, 1998). This task is based on the assumption that the offset of the vowel sound "uhhhh" is equal to the onset of articulation of the target stimulus. Mean initial phoneme duration was used in addition to mean naming latency as dependent variables. Kawamoto and colleagues (Kawamoto et al., 1998) showed the informativeness of this dependent variable. The duration of pronouncing a phoneme preceding an inconsistently pronounced vowel is longer than when the same phoneme precedes a vowel with a regular and consistent pronunciation. The finding was interpreted to mean that readers start articulation for a word as soon as the necessary information for the first phoneme is available.

Seventy-two monosyllabic, English, four-letter words were used as test items. The two independent variables of spelling-to-sound and sound-to-spelling consistency had each two levels, lexically consistent and inconsistent items. Neighborhood structure (Coltheart, Davelaar, Jonasson, & Besner, 1977; Grainger, O'Regan, Jacobs, & Segui, 1992) and subjective familiarity (taken from the MRC Psycholinguistic Database, 1987) were equated across the four sets of words. Words were also matched on various variables that are known to influence written word recognition, such as frequency in print (Kucera & Francis, 1967) and summed positional bigram frequency (Massaro, Jastrzembski, & Lucas, 1981; Massaro et al., 1980). The word sets were also matched on initial phonemes (i.e., an equal number of items with the same manner of articulation). All words were phonological consonant-vowel-consonant (CVC) words. Two postvocalic naming tasks were conducted: The first one was an immediate naming task, and the second one a delayed version with six different delays between 150 and 1,400 ms. This delayed naming task allows the participant to complete lexical access ("delays of 650 ms or greater," according to Goldinger, Azuma, Abramson, & Jain, 1997, p. 191), and any consistency effects could be attributed to postlexical processing.

The immediate and the delayed postvocalic naming task showed similar results (see Table 3.1 for an overview of all results). Sound-to-spelling consistency influenced initial phoneme duration of the response as well as its reaction time. Spelling-to-sound consistency only affected the initial phoneme duration of the response. There was no interaction between the two types of consistency. Delay in the delayed naming task shortened reaction times as delay was increased up to 1,150 ms. Most important, however, delay did also not interact with consistency. Following the logic of the delayed naming task (Balota & Chumbley, 1985; Forster & Chambers, 1973), it seems safest to conclude that the significant effects were at least partially produced by postperceptual processes.

TABLE 3.1
Results of Consistency Studies

Type of Task	DV	Consistency: Spelling-to-Sound Subjects	Consistency: Spelling-to-Sound Items	Consistency: Sound-to-Spelling Subjects	Consistency: Sound-to-Spelling Items
Immediate postvocalic naming task	RT	*ns*	*ns*	$p < .05$	*ns*
	IPdur	$p < .01$	*ns*	$p < .01$	*ns*
Delayed postvocalic naming task	RT	*ns*	*ns*	$p < .01$	*ns*
	IPdur	$p < .01$	*ns*	$p < .01$	*ns*
German fragmentation task	IT	$p < .05$	*ns*	*ns*	*ns*
	% err	*ns*	*ns*	$p < .05$	*ns*
	% T	$p < .01$	$p < .05$	$p < .01$	*ns*
English fragmentation task	IT	*ns*	*ns*	*ns*	*ns*
	% err	*ns*	*ns*	$p < .05$	*ns*
	% T	*ns*	*ns*	*ns*	*ns*
Lexical decision task	RT	—	—	*ns*	*ns*
Words	% err	—	—	*ns*	*ns*

Note. Dependent variables (DV) are mean reaction time (RT), mean initial phoneme duration (IPdur), mean level of correct identification (IT), mean error rate in percentage (% err), and overall mean performance (% T).

Replacing the voice key with digital offline processing, adding a new informative dependent variable—initial phoneme duration of the response, controlling for all previous confounds, and including delayed response conditions improved the validity of the naming task. With this improvement, no convincing evidence was found for consistency influences on word recognition. In successive studies, we also investigated whether consistency effects would occur in other tasks, such as perceptual identification and lexical decision, as well as in other languages, such as German. Do consistency effects differ in (shallow) orthographies, such as, for example, German, compared with inconsistent (deep) orthographies such as English and French (Ziegler, Jacobs, & Stone, 1996; Ziegler, Stone, & Jacobs, 1997)?

The next two experiments examined consistency in the fragmentation task (Snodgrass & Mintzer, 1993; Snodgrass & Poster, 1992; Ziegler, Rey, & Jacobs, 1998), which presents test words that are only partially displayed. Participants are instructed to type in a word as soon as they think there is enough information. There were eight stimulus levels, ranging from minimal information displayed to a presentation of the complete word. The level of information is increased systematically until the participant responds. This nature of the task makes the fragmentation task similar to speed-accuracy trade-off tasks (Ziegler et al., 1998). Both accuracy and how much stimulus information was presented when a response was made are necessary to describe performance.

For the German study, spelling-to-sound consistent items are produced at less informative levels and with a lower error rate than spelling-to-sound inconsistent items. The same results were found for sound-to-spelling consistency. Unfortunately, this result could be due to a difference in subjective familiarity because it could not be controlled for German (see Table 3.1 for detailed overview of results of the German and English fragmentation task).

When subjective familiarity was controlled in the English fragmentation study, there was no difference between consistent and inconsistent items of either type of consistency for level of correct identification. There was also no interaction between the two types of consistency for any of the dependent variables. However, words that have rimes that can be spelled in more than one way produce significantly higher error rates than words with rimes that are always spelled the same way.

A last study was conducted that investigated whether consistency influences lexical decision. Spelling-to-sound and sound-to-spelling consistency effects had been found for lexical decision for English and French (Stone et al., 1997; Ziegler et al., 1997). However, our word list eliminated the confounds in these previous studies (i.e., neighborhood structure and subjective familiarity). Given these constraints in controlling for a variety of variables, there was a limitation in constructing matching nonwords, and the design had to be reduced to just one independent variable, sound-to-spelling consistency. The 36 spelling-to-sound consistent words from the naming and English fragmentation studies were used. Half of them were sound-to-spelling consistent, the other half inconsistent.

Thirty-six four-letter, spelling-to-sound consistent, monosyllabic CVC nonwords were selected. All of the nonwords were created based on bodies of real words. A body of a monosyllabic word is the end of a word starting at the first vowel. An onset is the part of the word that precedes the body. All of the nonwords had bodies of monosyllabic four-letter words, but the onset of each was replaced by a new single consonant onset (e.g., SISK created out of DISK). The onsets used were the same as for the word items so that lexicality was not confounded with a certain onset. Half of the nonwords were sound-to-spelling consistent (e.g., _IFE in the nonword TIFE, based on FIFE, KNIFE, LIFE, STRIFE, WIFE), the other half is inconsistent (e.g., _AKE in the nonword PAKE, based on CAKE, BAKE, BRAKE, DRAKE, FAKE, FLAKE, LAKE, MAKE, QUAKE, RAKE, SHAKE, but also on ACHE and BREAK). Only bodies were used that were shared by words from the same consistency group. The word and nonword stimuli were matched on positional bigram frequency. Therefore, nonwords highly resembled English words in their orthographic structure. This should increase the reliance on phonological (or semantic) information to distinguish words from nonwords. Sublexical orthographic information could not be used to make a decision.

In the lexical decision task, none of the analyses for words showed a significant difference between sound-to-spelling consistent and inconsistent items. Words with a pronunciation that could be spelled multiple ways (e.g., MALL), and therefore resembled many different words, were not more difficult to reject than nonwords that have a pronunciation that can only be spelled in one way (e.g., CAPE; see Table 3.1 for an overview of the results of the lexical decision task).

In sum, the existing literature and our current experiments provide very little evidence that lexical consistency influences word recognition (lexical access). There is little evidence that the observed consistency effects are caused by perceptual influences on word recognition. We believe that the reason for this outcome is that consistency—as currently defined in terms of word neighbors that share the body or its phonological equivalent, the rime—is not the appropriate measure of sublexical influences in reading. We believe that fluency, described earlier in the account of spelling-to-sound influences, is a more psychologically valid description of these influences (Massaro & Cohen, 1994; Venezky & Massaro, 1987). Although our fluency measure has been formalized only for spelling-to-sound influences, we describe how it can be easily extended to sound-to-spelling influences.

Fluency and Modeling Sound-to-Spelling Influences

Independent of any methodological issues in the previous empirical studies, there are two important questions to address. First, if indeed sound-to-spelling consistency influences written word recognition, what is the best description of this sound-to-spelling structure? Second, if it is psychologically functional in written word recognition, is feedback necessary to account for this influence or can this influence be accounted for in a feed-forward model?

With respect to the description of consistency descriptions, the sound-to-spelling consistency manipulation in our experiments was based, as in Stone et al. (1997), on the body or rime of a word. This definition and operationalization of orthographic feedback consistency is only one of the many possible ones. A different method of segmenting the spoken language would lead to different measures of feedback consistency. The type of definition that is most psychologically real would also inform the debate of written word recognition in terms of whether words are read via sublexical letter patterns or whether they are read as simply being selected from activated words in the reader's lexicon.

Given the previous formalization of spelling-to-sound fluency, we now develop an analogous fluency measure for sound-to-spelling consistency (Jesse, 2000; Massaro & Jesse, 2000). Any database used to compute fluency of the mapping from spelling to sound can be used to compute the mapping from sound to spelling. Instead of asking how likely a grapheme is pronounced as a phoneme, we ask how likely a phoneme is spelled by a grapheme. This might be a better measure of sound-to-spelling influences than the current ones. The fluency score of a phoneme-to-grapheme correspondence is based on the number of occurrences of the mapping relative to the sum of all mappings for the phoneme. The zero-order measure would force each phoneme into a single letter, whereas the first-order measure would allow the phoneme to be mapped into multiletter graphemes. An example to illustrate is the mapping of the word THIN: For the first-order fluency measure, the phonemes of THIN (i.e., /θIn/) have each to be mapped into one grapheme: /θ/ would map into TH, /I/ to I, and /n/ to N. The second-order fluency measure would consider the position of the phonemes in the word. For all versions of the fluency measure, the fluency score for a whole word would be the average of the fluency scores for its constituent parts.

A similar development process using our earlier approach to spelling-to-sound correspondences (Venezky & Massaro, 1987) was employed by Perry, Ziegler, and Coltheart (2002) to create a comparable fluency measure for sound-to-spelling correspondences. Our measure differs from Perry et al.'s (2002) in that it is calculated not on the basis of all monosyllabic words, but on all words. Also their use of a truncated frequency measure is problematic, and we think that our measure based on logarithmic frequency deals better with the problem of inflating the measure by the inclusion of a few single high-frequency items. These two fluency measures also differ in their definitions of how different orders of fluency are determined.

Our fluency metric also differs significantly from the definition of sound-to-spelling consistency used by Stone et al. (1997). Because their analysis is based on lexical consistency, potential spelling patterns are limited to existing words in the language rather than potentially legal sublexical spellings. Furthermore, their definition of sound-to-spelling consistency precludes certain spelling patterns for spoken language segments even though these would be admissible in the language. For example, they claim that /ob/ can be written only as OBE. This is because consistency is defined in terms of the rime or body of existing words in the lexicon (Bowey, 1990, 1993; Treiman, 1994; Treiman & Chafetz, 1987; Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995; Treiman &

Zukowski, 1988). The word GLOBE would be broken up into the onset /gl/ and the rhyme /ob/. Thus, they ask, what are the possible spellings in English of /ob/? Because all monosyllabic words that end in /ob/ are spelled OBE, GLOBE is categorized as a sound-to-spelling consistent word, which should produce faster reaction times in a lexical decision task. In contrast, the speech segment /o/ can be spelled in many different ways, such as OA as in the word MOAT, OE as in HOE, OW as in GROW, or O_E as in VOTE. By this criterion, OBE would not be sound-to-spelling consistent. The sublexical unit at which consistency is defined is crucial for the word's classification as consistent or inconsistent. An appropriate definition is needed to describe and predict reading performance adequately.

The second issue in modeling sound-to-spelling consistency effect is what structure a model needs to account for it. Any influence of how a phonological segment is spelled is usually implemented as an interaction among different levels in a connectionist model. To understand how our feed-forward model is sufficient to describe sound-to-spelling influences in word recognition, it is valuable to understand how it would work in a feedback model. Stone and colleagues (1997) inappropriately define feedback models as all models that can behave as if they would contain a feedback loop. This can be realized through interactive activation, where information between layers is transmitted via a forward and a feedback loop. A letter string is presented, which activates the letter representation. Processing of this letter representation activates phonemes, supposedly on the basis of something like the influence of our fluency variable but most commonly described as consistency measure. This activation of phonemes in turn activates a set of spelling patterns. These spelling patterns then feed back to the letter representation and activate it accordingly. To the extent that the phoneme level is mapped into a single spelling pattern, the letter representation would be greatly biased to this spelling pattern. To the extent that the phoneme level is mapped into several different spelling patterns, the letter representation would be much noisier and therefore less informative about which written word was presented. This description of how feedback consistency would work in a connectionist model is exactly analogous to how context is assumed to operate in the interactive activation model.

Peereman et al. (1998) stated in their article on sound-to-spelling consistency that the "purpose of the present research (on the existence of the sound-to-spelling consistency effect) is to explore whether word recognition, as indexed by the lexical decision task, entails interactive activation between orthographic and phonological codes" (p. 152). As can be seen in the account given by the FLMP, an influence of sound-to-spelling consistency, if one exists, does not require interactive activation, and therefore the test of sound-to-spelling consistency is not a test of interactive activation. Stone et al. (1997) acknowledge that their results do not necessarily require a model with a feedback loop. It also can be implemented with a "simple-match procedure" (Stone et al., 1997, p. 353), in which the processing of one source of information is not altered by any information flowing back from another source of information (Massaro, 1979; Paap, Newsome, McDonald, & Schvaneveldt, 1982). Stone and colleagues still call this kind of model feedback, although the flow of information is strictly forward. We suggest that this blurring of the difference between *feedback* and *feed-forward* is inappropriate.

Postulating this source of information is not completely a post hoc explanation because, in addition to orthography itself (e.g., Seidenberg & Tanenhaus, 1979; Tanenhaus, Flanigan, & Seidenberg, 1980; Whatmough, Arguin, & Bub, 1999), sound-to-spelling correspondences have been shown to influence auditory recognition (Ziegler & Ferrand, 1998). Ziegler and Ferrand (1998) found for auditory word recognition that French words with phonological rimes that can be mapped into multiple spellings produce longer auditory lexical decision latencies and more errors than sound-to-spelling consistent words. The FLMP does predict that the relationship between orthography and phonology plays a role in auditory word perception as it assumes a general algorithm across modalities. Therefore, it is not justified to say that the FLMP does not "naturally predict a feedback effect" (Ziegler et al., 1997, p. 535). Contrary to Peereman et al. (1998), the existence of feedback consistency does not require a model of interactive activation. The FLMP can account for a feedback consistency effect by assuming that sound-to-spelling correspondences are influential. As the word's letters are recognized, their corresponding pronunciations are made available, which then provide independent information about which letters and word is present. We do not need a feedback loop to explain the feedback consistency effect. The FLMP and connectionist models (such as, e.g., the multiple read-out model including phonology by Jacobs, Grainger, Rey, & Ziegler, 1998), therefore, make similar predictions.

However, it has been shown in several other studies that it is not necessary to assume interactive activation to explain common phenomena in language processing (Massaro, 1989; Massaro & Cohen, 1991). The FLMP can, for example, better account for the influence of context on stimulus identification without assuming a feedback connection (Massaro & Cohen, 1991, 1994; Massaro & Friedman, 1990) than interaction models with feedback. It can also account better for the influences of bottom-up and top-down sources of information in speech perception (Massaro, 1989) than its interactive-activation opponent, the TRACE model (McClelland & Elman, 1986).

More recent evidence comes from a study of masked priming in Hebrew, obtaining about 100,000 data points from 160 participants (Frost, 2003; Frost, Ahissar, Gotesman, & Tayeb, 2003). In the masked priming study, a short presentation of a priming word is preceded by a mask and followed by a test word. A lexical decision is made based on the test word. Participants do not report the priming word supposedly because of the preceding mask and the test word functioning as a backward mask. The priming word is either similar to or different from the test word in spelling or pronunciation, or both. As expected, a test that differs by two letters from the prime is responded to more slowly in the lexical decision task than if the prime differs by just a single letter. In both cases, the prime was homophonic with the test. This effect of orthography shows that the lexical decision task is sensitive to the letter processing of the test word.

Effects of phonology were also apparent. The homophonic (i.e., identical sounding) prime (e.g., KLIP as a prime for CLIP) facilitates the response to the test word in the lexical decision task relative to a priming word that differs in its pronunciation by the initial phoneme (e.g., PLIP as a prime for CLIP). This klip-CLIP priming effect as originally found by Lukatela and colleagues (Lukatela, Frost, & Turvey, 1998) had been criticized because replications usually failed (Coltheart et al., 2001). It has been argued that it could be observed only under certain light conditions. However, Frost (2003) shows in his replication in Hebrew that this phonological priming effect can be found for a wide range of levels of luminance and stimulus onset asynchronies (SOAs). This strong result shows that prelexical phonological effects appear to be influential very early in processing, if we can assume that the lexical decision task is measuring this early processing. A postperceptual process might also be responsible in that the test word might be recognized without any influence from the prime but that the prime speeds up the response selection and production process. Somehow a similar sounding word to the test would speed up lexical decision relative to a dissimilar sounding word. A control analogous to the delayed naming task would be to present the prime just after the test word is recognized (about 200 ms after its onset) and determine whether the nature of the prime is still influential.

The phonological effects in masked priming, if accepted to reflect early processing of the test word, are strong evidence against interactive activation. The reason is that there would not be sufficient time for feedback and interactive activation to occur. Frost (2003) makes an analogous argument against the dual route cascaded (DRC) model because the orthographic lexicon would have to be accessed before phonological information gets activated in the DRC.

CONCLUSION

We began with acknowledging that reading was magical but composed of a magic that was well studied and, perhaps, even fairly well understood. We hope that our guided travel through the research and theories about word recognition have illuminated the complexity involved when multiple sources of information are influential. To support our road map, we presented evidence that visual word recognition relies, just like any other form of pattern recognition, on the successful exploitation of multiple sources of information. We discussed the contribution of visual, orthographic, and phonological sources of information to the visual word recognition process. We showed that some old ideas, such as reading words as wholes or without the influence of spoken language, have been successfully defeated. However, they have been replaced with new controversies that are currently unresolved. Such controversies include the question of the appropriate sublexical units used in reading and the role of sound-to-spelling mappings. We described a series of experiments to shed light on these questions. We can conclude that although phonological information in general certainly plays a role in written word recognition, there is little evidence that consistency influences word recognition. We believe that a reason for this might be that the definition of consistency is based on the body and rime unit, which is not the appropriate sublexical unit in reading. Fluency, as developed by Venezky, is a more psychologically valid description of sublexical phonological influences (Massaro & Cohen, 1994; Venezky & Massaro, 1987). Fluency had previously only been defined as a spelling-to-sound measure. We proposed a new sound-to-spelling version of fluency. Finally, we outlined a feed-forward model of visual word recognition, the fuzzy logical model of perception, that can also account for sound-to-spelling fluency effects. Sound-to-spelling effects do not require interactive activation to be accounted for by a model. Therefore, their value to discriminate between current competing model candidates in visual word recognition is low.

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