Journal of Experimental Psychology:
Human Perception and Performance
1979, Vol. 5, No. 4, 595–609

Letter Information and Orthographic Context in Word Perception

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Theories of word perception in reading can be categorized in terms of the assumption made about whether or not a word context modifies the feature analysis of its component letters. Independence theories assume that the visual information passed on by feature analysis is independent of word context. Nonindependence theories assume that a word context directly influences visual analysis. Some nonindependence theories have assumed that word context enhances feature analysis of letters, others have assumed that word context overrides feature analysis of letters, and some have assumed that word context directs which letters are analyzed. The present experiment provided a critical test between the two classes of theories by independently varying orthographic context and visual letter information in a letter recognition task. The results contradict the qualitative predictions of the class of nonindependence theories and are accurately described by a quantification of independence theory.

To what extent is word perception mediated by letter perception? This question has been debated since the inception of reading-related research about one century ago (Cattell, 1886; Gibson & Levin, 1975; Huey, 1908/1968; Massaro, 1975b). Luckily, almost every stand on this issue can be subsumed under one of two general theories. In letter-unit theory, word perception follows naturally from perception of the letters in the word and the appropriate knowledge in the mind of the reader. In word-unit theory, letters composing a word make up a unique configuration that is perceived as a total whole. These two theories have at various times served as the basis for the phonics and sight-word methods of reading instruction (Chall, 1967; Smith, 1971). The experimental and pedagogical debate has been rekindled in the last decade partly as a result of the recent proliferation of reading-related research.

These two theories can be contrasted within a generally accepted view of word perception in reading. A printed pattern is first transduced by the visual receptor system, and featural analysis makes available a set of visual features. The word perception process combines this visual information with other nonvisual knowledge and arrives at a perceptual experience of the printed pattern. The two theories differ in terms of whether or not the feature analysis of each letter is independent of the orthographic context imposed by the surrounding letters. The letter-unit theory claims that feature analysis is not modified by orthographic context, whereas the word-unit theory claims just the opposite. The critical test proposed here centers around the issue of whether or not visual letter information and orthographic context

This research was carried out at the Wisconsin Research and Development Center for Individualized Schooling and was supported in part by funds from the National Institute of Education, U.S. Department of Health, Education, and Welfare.

David Klitzke programmed the experiment, tested the subjects, and carried out most of the data analyses. Michael Cohen contributed to some of the latter. Gregg Oden and Glen Taylor provided helpful reactions to the study.

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make independent contributions to word recognition. Given that feature analysis is not modified by orthographic context in the letter-unit theory, their contributions are predicted to be independent. According to the word-unit theory, the feature analyses of letters are modified by orthographic context, and, therefore, their contributions are not independent. The contrasting theories can be clarified by an analysis of recent formulations of specific models. Nonindependence views have taken the form of feature analysis differences, higher order units, and hypothesis-testing mechanisms.

A letter in a word is recognized more often than a letter presented alone or presented in a nonword under the same conditions (Johnston & McClelland, 1973; Reicher, 1969; Thompson & Massaro, 1973). This result obtains even though a simple guessing advantage for words is precluded by constraining the response alternatives. One of the primary interpretations of these findings is that the word context enhances the visual feature analysis of the component letters. If feature analysis were a limited-capacity process and subject to attentional control, then it might be expected that the familiarity of a word pattern would produce better feature analyses of the component letters. After an exhaustive and careful review of the literature, Krueger (1975, Table 1) allows the possibility that the familiarity of orthographic context might influence the feature analysis stage. According to this interpretation, readers would have a greater number of features and/or a better resolution of the features in a word than in a nonword context. This would mean that readers should be able to report more accurate detail about the visual characteristics of the letters in a word than in a nonword context.

In the second type of nonindependence models, higher order units intervene in the processing sequence and change the features and/or the featural analyses that are employed. As an example, some models assume specific memory codes for spelling pattern units, and some visual features are defined in terms of these higher order units (Juola, Leavitt, & Choe, 1974; LaBerge & Samuels, 1974; Neisser, 1967; Smith & Haviland, 1972; Taylor, Miller, & Juola, 1977; Wheeler, 1970). As an example, the frequent spelling pattern *st* could function as a perceptual unit, and the top extent of the *s* and the horizontal cross of the *t* might function as a single supraletter feature. In this case, perception of the spelling pattern *st* might be easier than perception of either letter presented alone, since the presence of supraletter features gives the reader additional visual information (Wheeler, 1970).

In contrast to assuming a facilitative effect of higher order units, other models in this set assume that word context can override the perception of the letters that make it up. In Johnson's (1975) model, for example, the feature set assigned to a letter sequence is determined by the entire sequence and higher order memorial feature sets. In this case a letter will be assigned different features in different orthographic contexts. Johnson's model makes the prediction that the higher order memorial feature sets camouflage the component letters, and, therefore, readers might know less about the visual characteristics of a particular letter in a word than that same letter presented alone or in a nonword string.

A final class of nonindependence models assumes that expectancy and hypothesis testing play an important role in the initial stage of visual analyses. In hypothesis-testing models, the current hypothesis directs feature analysis (Goodman, 1976a, 1976b; Wheeler, 1970). In the hierarchical feature-testing model of Wheeler (1970), for example, the detection of some features guides the detection of other features. Osgood and Hoosain (1974) have also made this type of nonindependence assumption in their view of word perception. Their specific idea of nonindependence involves the derivation of the meaning of the word to feed back and influence the information passed on by peripheral sensory processes (feature detection in the present framework). This assumption is similar to an

observing response model (Broadbent, 1967) in which the feature detection is biased by context and the solution given by Erdelyi (1974) for findings in the perceptual defense literature. The distinguishing attribute of this class of models is that feature processing is directly dependent on the guiding hypothesis; for example, a hypothesis that the word is *Philadelphia* might guide the feature analysis to test for an initial capital letter and a relatively long word. Accordingly, the visual features passed on by feature analysis vary as a function of the guiding hypothesis. The reader should know more about the visual characteristics of the segment of the word that are relevant to the current hypothesis and less about the visual characteristics that are not relevant.

The current analysis makes transparent that nonindependence views of reading do not make the same predictions about how visual feature analysis is modified by orthographic context. However, in contrast to independence models, all nonindependence models assume that orthographic context changes the visual information passed on by feature analysis to the next stage of word recognition.

Independence models follow in the tradition of Morton's (1969) logogen model in which higher order context and visual information provide independent contributions to word recognition. Broadbent's (1971) model of the biasing effects of context and probability also qualifies as an independence model, since changes in these variables do not modify the intake of visual information. Although the issue of orthographic context was not addressed in these models, another independence model has been articulated in terms of word recognition as a direct consequence of featural information and orthographic context (Massaro, 1973, 1975a; Thompson & Massaro, 1973). The model was developed on the basis of experiments carried out using variants of the Reicher paradigm (Reicher, 1969; Wheeler, 1970). Subjects were presented with either a word or a single letter for a short duration followed immediately by a masking stimulus and two response alternatives. The response alternatives would both spell words in the word condition; for example, given the test word WORD, the response alternatives ---*D* and ---*K* would be presented. The corresponding letter condition would be the test letter *D* followed by the response alternatives *D* and *K*. Performance was about 10% better in the word than in the single-letter condition.

Given the two-alternative forced-choice control, it was argued that the reader was able to utilize orthographic context to eliminate possible alternatives during the perception of the test display before the onset of the masking stimulus (Thompson & Massaro, 1973). As an example, given recognition of the context WOR and a curvilinear segment of the final letter, the reader could narrow down the alternatives for the final letter to D, O, and Q. Given that O and Q are orthographically illegal in the context WOR__, D represents an unambiguous choice. The reader will therefore perceive the word WORD given just partial information about the final letter. If the reader has recognized the same curvilinear segment in the corresponding letter condition, however, any of the three letters (D, O, and Q) are still possible, and the perceptual synthesis will result in D only one out of three times. What is critical in this analysis is that a word advantage is obtained even though the visual information available to the perceptual process is equivalent in the word and letter conditions. The orthographic context of the word simply provides an additional but independent source of information. The featural information available to the recognition process does not change with changes in orthographic context. In this view, although orthographic context facilitates word perception, it does not modify the feature analysis of the printed pattern.

An experiment was carried out to test the differences between these two general classes of theories. The logic of the experiment centered on the question of whether context and featural processing make independent contributions to letter per-

Figure 1. The 96 test items in the *e-c* stimulus set generated by the factorial combination of six bar lengths of the test letter, four serial positions of the test letter, and four orthographic contexts.

ception. The experiment involved the independent variation of the visual information about a letter and its orthographic context in a letter perception task. Consider the lower case letters *c* and *e*. It is possible to gradually transform the *c* into an *e* by extending the horizontal bar. To the extent that the bar is long, the letter resembles *e* and not *c*. If the letter is now presented as the first letter in the context *-oin*, the context would support *c* but not *e*. Only *c* is orthographically legal in this context, since three consecutive vowels would violate English orthography. This condition is defined as *e* illegal and *c* legal ($\bar{e} \wedge c$). Only *e* is valid in the context *-dit*, since the cluster *cd* is an invalid initial pattern in English. In this case, the context *-dit* favors *e* ($e \wedge \bar{c}$). The contexts *-tso* and *-ast* can be considered to favor neither *e* nor *c*. The first remains an illegal context whether *e* or *c* is present ($\bar{e} \wedge \bar{c}$), and the second is orthographically legal for both *e* and *c* ($e \wedge c$).

The experiment factorially combined six levels of visual information with these four levels of orthographic context, giving a total of 24 experimental conditions. The bar length of the letter took on six values going from a prototypical *c* to a prototypical *e*, as shown in Figure 1. In addition, the figure shows that the test letter was also presented at each of the four letter positions in each of the four contexts. A single test string was presented for a short duration followed after some short interval by a masking stimulus composed of random letter features. In all cases, the subject indicated whether an *e* or *c* was presented in the test string.

Nonindependence theories assume that featural processing is *not* independent of context. It follows that any model assuming independent contributions of each must fail. Given that no quantitative formulations of the nonindependence hypothesis are currently available, we are limited to testing the quantitative predictions of an independence model. If the independence model describes the results reasonably well, this provides evidence against the class of nonindependence theories until an equally parsimonious nonindependence model can be developed and tested favorably against the results.

Although a quantitative test of nonindependence models is not available, the present experiment also provides a direct qualitative test of this class of models. As noted in the previous discussion, all nonindependence models predict that orthographic context influences the degree of resolution of visual feature analyses. One direct measure of visual resolution in the present experiment is the degree to which the reader can discriminate the bar length of the test letter. This discrimination can be indexed in the present experiment by the degree of differential responding to the successive levels of the bar length of the test letter. Better resolution of the test letter is assumed to occur to the extent that the subject responds *e* to one length and *c* to another. In the ($e \wedge c$) context, both letters spell words, whereas neither letter spells a word in the ($\bar{e} \wedge \bar{c}$) context. If the word context influences letter resolution as assumed by the class of nonindependence theories, then the discrimination of bar length should differ in the word and nonword contexts. If it does not, this would provide a critical failure of nonindependence theories.

Method

Subjects

Eleven subjects were tested for 4 consecutive days. The subjects were students in an introductory psychology course who volunteered to participate in the experiment for extra course credit. Up to four subjects could be tested in parallel in separate rooms.

Procedure

The test display was presented for 30 msec followed after a variable blank interval by a 30-msec masking display. The blank interstimulus interval (ISI) was 5, 40, 95, or 210 msec. Each trial began with a 500-msec fixation point followed by the test and masking displays. Subjects had up to 4 sec to respond by pushing one of two keys. The next trial began 500 msec after this 4-sec period or 500 msec after the last subject responded.

Two sessions were given per day. Each session consisted of 56 practice trials in which the test letter was presented in a dollar sign ($) context and 384 experimental trials. Four letter positions, 4 contexts, 6 bar lengths of the test letter, and 4 interstimulus intervals combine to give 384 trials with one observation per condition. A second stimulus set of items was generated and tested using the letters *n* and *h*. The length of the vertical line in the test letter and the orthographic context were varied exactly analogous to the *e-c* stimulus set. Figure 2 presents the items used in the *h-n* stimulus set. Only one letter was tested per day, giving 2 test days for each stimulus set. Subjects were instructed to indicate whether they saw an *e* or *c* given the *e-c* stimulus set and an *h* or *n* given the *h-n* stimulus set. They were told to make the best choice based on what they saw.

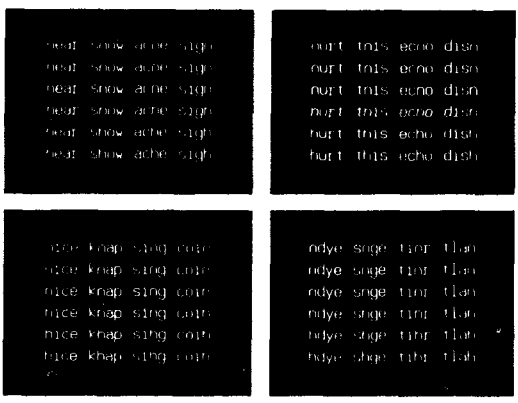

Figure 2. The 96 test items in the *h-n* stimulus set generated by the factorial combination of six bar lengths of the test letter, four serial positions of the test letter, and four orthographic contexts.

Stimuli

The visual displays were generated under computer control and were presented on Tektronix Monitor 604 oscilloscopes with a p-31 phosphor (Taylor, Klitzke, & Massaro, 1978). Figures 1 and 2 were made from reproductions of photographs of the actual displays used in the experiments. The alphabet consisted of lowercase nonserified letters closely resembling the type font Univers 55. The lines were composed of dots so closely spaced that individual dots were not discriminable. The line segments comprising the letters appeared continuous. The ratio of the height of ascenders and descenders to *x*-height letters was 3:2 as was the ratio of the height of an *x*-height letter to its most usual width. Interletter spaces were about .38 of the width of an *x*-height letter. The four-letter items subtended about 1.5° of visual angle horizontally, and the distance from the top of an ascender to the bottom of a descender was about 1°. The masking stimulus was composed of a random mixture of the component features of the letters. The average area, intensity, and density of the masking display were equivalent to the test display.

To equate the stimulus intensity and duration of the test letter in each context condition, it was necessary to plot that letter with the same number of points and in the same amount of time independent of the other letters in the display. This was accomplished by normalizing the plotting time so that smaller letters (e.g., *r*) would be plotted in the same amount of time as larger letters (e.g., *m*). This involved executing instructions that did not affect the display screen but that required the same execution time and that were interspersed with actual point intensification instructions.

Results

c-e Stimulus Set

Figure 3 presents the average probability of an *e* response as a function of the bar length of the test letter and the orthographic context. The probability of an *e* response increased with increases in the bar length of the test letter from .12 with the most *c*-like to .85 with the most *e*-like test letter, $F(5, 50) = 120$, $p < .001$. The orthographic context also influenced the likelihood of an *e* response, $F(3, 30) = 12.5$, $p < .001$. The $(e \wedge \bar{c})$ context produced .53 *e* responses, whereas the $(\bar{e} \wedge c)$ context produced only .37 *e* responses. The $(e \wedge c)$ and the $(\bar{e} \wedge \bar{c})$ contexts did not differ from one another, producing .46 *e* responses. The interaction of bar length and context was statistically significant,

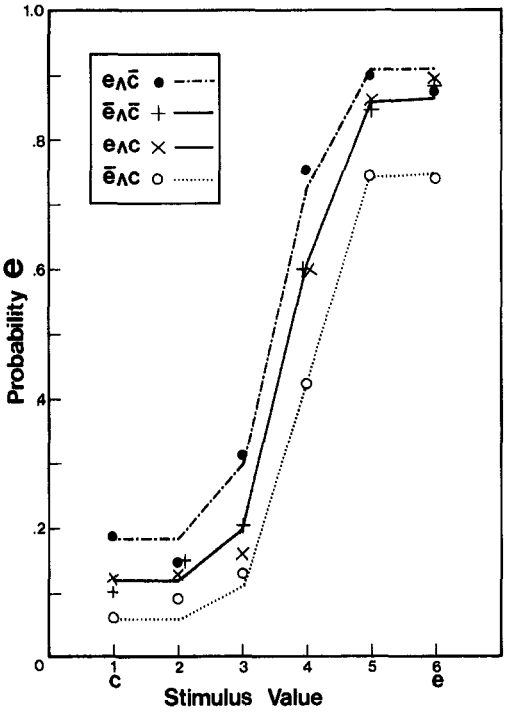

Figure 3. Observed (points) and predicted (lines) probabilities of an *e* response as a function of the stimulus value of the test letter and the orthographic context.

$F(15, 150) = 7.1$, $p < .001$. The magnitude of the effect of context was largest at the intermediate levels of bar length of the test letter.

The variable blank interval between the test and masking stimulus (ISI) had a large effect on the discriminability of the bar length of the test letter; the interaction of the bar length and ISI was significant, $F(15, 150) = 22.8$, $p < .001$. Figure 4 shows that the responses became more neutral as ISI decreased. Although the Context × ISI interaction was significant, $F(9, 90) = 2.3$, $p < .05$, there was no systematic change in the magnitude of the effect of context as a function of ISI. No other source of variance was statistically significant.

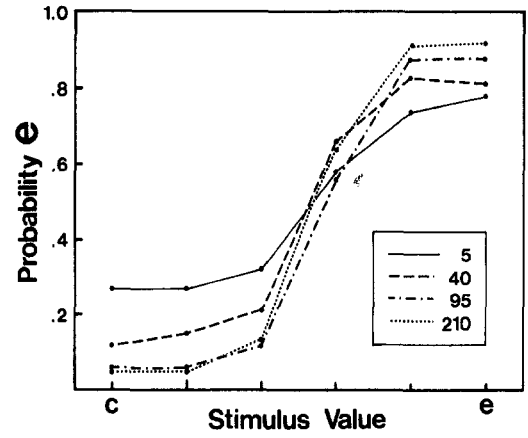

Figure 4. Probabilities of an *e* response as a function of the stimulus value of the test letter and the interstimulus interval in msec.

An additional analysis was carried out to include the analysis of the effect of the four test sessions. The effect of context decreased with practice, leveling off in the third session at about half of what it was in the initial test session, $F(9, 90) = 5.2$, $p < .001$. No other interaction with sessions was significant in the analysis. These results show that the results observed here appear to hold for either relatively naive or relatively practiced subjects.

It is also important to evaluate the

Table 1
Average Probabilities of an e *as a Function of the Orthographic Context and Serial Position*

	Serial position							
	First		Second		Third		Fourth	
Context	Item	*P*	Item	*P*	Item	*P*	Item	*P*
Both *e* and *c* illegal	__tsa	(.50)	a__sr	(.45)	dt__u	(.48)	tla__	(.45)
Both *e* and *c* legal	__ast	(.52)	s__ar	(.47)	du__t	(.46)	tal__	(.41)
c legal; *e* illegal	__oin	(.29)	s__um	(.47)	pa__k	(.36)	zin__	(.35)
e legal; *c* illegal	__dit	(.58)	s__ll	(.56)	sl__d	(.55)	pan__	(.43)

degree to which the legality of the orthographic context had consistent effects across the different items. Table 1 presents the average probability of an *e* response for each of the 16 test items. The context effect was reasonably consistent across the 4 items in each context condition. There were no significant differences between both the legal and both the illegal members of each pair of test items. One test item of the $\bar{e} \wedge c$) context did not produce the expected result. Although *e* is illegal in the context *s-um*, the probability of an *e* response to this item was as high as it was to the comparable ($\bar{e}$ and $\bar{c}$) and (*e* and *c*) contexts.

The magnitude of the context effect was also significantly attenuated in final position. Because of the constraints of natural orthography, it was impossible to find contexts that were truly orthographically illegal for one of the test letters but legal for the other. For example, the context pane supports *e*, since *pane* spells a word but the alternative *panc* is not orthographically illegal. In agreement with this orthographic possibility, the probability of an *e* response was not significantly higher in this context than in the context *tal-*, in which both *c* and *e* spell words. The context *zin-* produced an effect of lexical context over and above that of orthographic regularity, however. Although *zine* is orthographically legal, the probability of an *e* response given this context was 6% less than it was in the context *tal-*. Therefore, subjects were more likely to read a *c* in the context *zin-* than they were in the context *tla-*, *tal-*, or *pan-*.

n-h Stimulus Set

Figure 5 presents the average probability of an *h* response as a function of the bar length of the test letter and the orthographic context. The probability of an *h* response increased with increases in the bar length of the test letter from .22 with the most *n*-like letter to .89 with the most *h*-like test letter, $F(5, 50) = 215$, $p < .001$. The orthographic context also influenced the likelihood of an *h* response, $F(3, 30) = 47.9$, $p < .001$. The $(h \wedge \bar{n})$ context

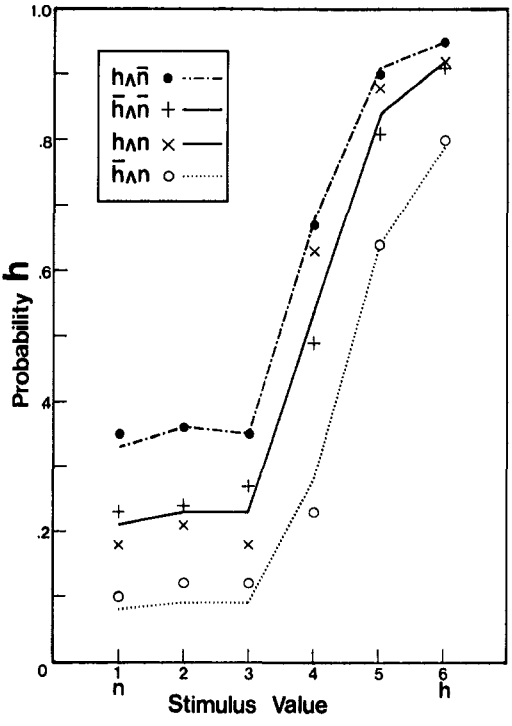

Figure 5. Observed (points) and predicted (lines) probabilities of an *h* response as a function of the stimulus value of the test letter and the orthographic context.

produced .60 *h* responses, whereas the $(\bar{h} \wedge n)$ context produced only .34 *h* responses. The interaction of bar length and context was statistically significant, $F(15, 150) = 14.4$, $p < .001$. The magnitude of the effect of context was largest at the intermediate levels of the length of the bar of the test letter.

The variable blank interval between the test and masking stimulus (ISI) had a large effect on the discriminability of the length of the bar of the test letter; the interaction of bar length and ISI was significant, $F(15, 150) = 50$, $p < .001$. Figure 6 shows that the responses became more neutral as the ISI was increased. There was a significant decrease in the magnitude of the context effect with increases in the ISI, $F(9, 90) = 8.4$, $p < .001$. The difference between the $(h \wedge \bar{n})$ and $(\bar{h} \wedge n)$ contexts was .35 at an ISI of 5 msec and decreased with increases in ISI to .30, .26, and .14 at ISIs of 40, 95,

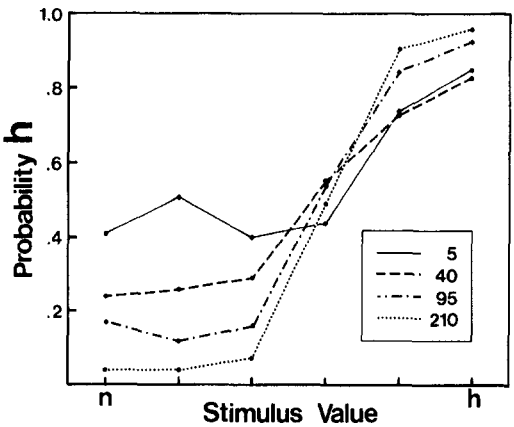

Figure 6. Probabilities of an *h* response as a function of the stimulus value of the test letter and the interstimulus in msec.

and 210 msec, respectively. None of the other sources of variance was statistically significant.

The analysis including sessions as an independent variable revealed a significant interaction of sessions and context, $F(9, 90) = 3.3$, $p < .005$. The effect of context decreased gradually over the four sessions leveling off at about two thirds of the size of the effect in the initial session. No other interaction with sessions was significant in the analysis. Even though practice may attenuate the context effect, it does not change the manner in which context interacts with other variables such as stimulus information.

Table 2 presents the average probability of an *h* response for each of the 16 test items. For each of the four serial positions, there was no difference between the responses to both legal and both illegal test strings. In all cases when *n* spelled a word in the context and *h* did not, the probability of an *h* response was significantly lower than in the both legal or both illegal contexts. This result held even in the context *-ice* in which *h* is not strictly. illegal as it was in the other contexts When *h* spelled a word and *n* did not ($h \wedge \bar{n}$), the probability of an *h* response was greater than in both legal and both illegal contexts except at Serial Position 1. At this serial position, the context *-urt* is not illegal for the letter *n*, and it appears that the additional lexical constraint of *h* was not sufficient to override the orthographic legality of *n*. In summary, in the six cases in which one alternative spells a word and the other is strictly illegal, all gave strong context effects. In the two cases in which both letters were orthographically legal but only one spelled a word, a context effect was found in just one. Therefore, there is some evidence that at least some of the contextual effects were due to orthographic regularity in addition to lexical constraints.

Discussion

The results showed large effects of stimulus information and orthographic context on the identification of the test letter. The significant interaction of these two variables revealed that the magnitude of the context effect was largest at the more ambiguous levels of stimulus information. Discriminability of the test letter increased with the perceptual processing time available before the onset of the

Table 2
Average Probabilities of an h *as a Function of the Orthographic Context and Serial Position*

	Serial position							
	First		Second		Third		Fourth	
Context	Item	*P*	Item	*P*	Item	*P*	Item	*P*
Both *h* and *n* illegal	__dye	(.50)	s__ge	(.47)	ti__r	(.50)	sib__	(.50)
Both *h* and *n* legal	__ear	(.50)	s__ow	(.48)	ac__e	(.52)	sig__	(.51)
n legal, *h* illegal	__ice	(.34)	k__ap	(.41)	si__g	(.33)	coi__	(.26)
h legal, *n* illegal	__urt	(.51)	t__is	(.68)	ec__o	(.58)	dis__	(.60)

masking stimulus. The orthographic context effect also decreased with increases in processing time for the *h-n* but not the *e-c* stimulus set. Finally, although the context effect decreased with experience in the experiment, it was still highly significant on the 4th day of the experiment. In the following discussion, a prediction of the class of nonindependence models will be tested against the results of the experiment. A quantification of the independence model will then be developed and tested against the observed results.

Nonindependence Models

Although a quantification of a nonindependence model is not available for test, the experiment offers a model-free test of the nonindependence assumption. The visual resolution of the test letter should be critically dependent on the orthographic context according to nonindependence models. In the present experiment, the degree to which the reader can discriminate the bar length of the test letter is a direct measure of visual resolution. Discrimination is good to the extent that the reader responds differentially to the successive levels of bar length. The test of nonindependence models, therefore, involves asking whether discrimination varies as a function of orthographic context. The response probabilities cannot always be taken as a direct index of discriminability, however, since the different contexts also had a large effect on response probability. It is necessary to define an explicit model of sensory processing and decision processing in the task to derive valid measures of the discriminability of the bar length. One model is based on an extension of the substantial assumptions of Thurstone's paired-comparison model or signal detection theory. According to this model, it is assumed that each bar length of the test letter produces some perceived value of bar length that is normally distributed. It is further assumed that the means of the distributions for the different bar lengths can differ from one another but that the variances are equal to one another.

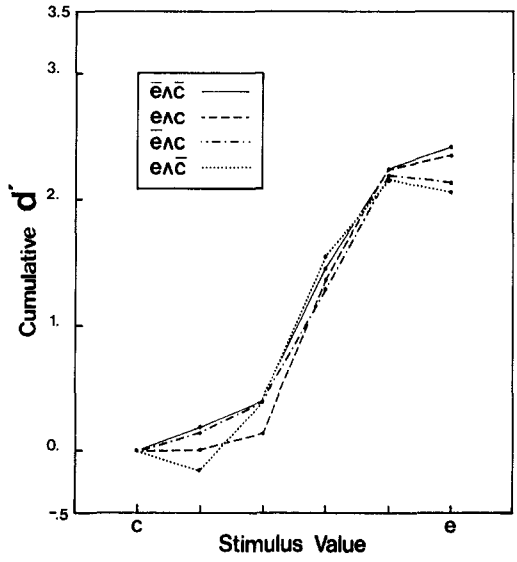

Figure 7. Cumulative d' values for the *e-c* letter set as a function of the stimulus value of the test letter and the orthographic context.

According to this model, an index of the discriminability of the bar length of the test letter is given by d' and can be derived from the response probabilities (Braida & Durlach, 1972). The probabilities of responding *e* to each of the six levels of bar length are transformed to *z* scores. The d' value between two adjacent levels of the bar length is simply the difference between the respective *z* scores. For example, if the subject responded *e* 5% and 15% to the most *c*-like and next most *c*-like test letter, respectively, the *z* scores would be -1.65 and -1.04. The d' value would, therefore, be .61 (The value is positive, since d' is a measure of the positive difference between the means of the respective normal distributions.) Adding these successive d' distances gives a cumulative d' discrimination function. The subject shows good discrimination of bar length to the extent that d' values between successive lengths of the test bar are large.

Figure 7 gives the cumulative d' functions for the *e-c* stimulus set. This function was derived from the average response probabilities given in Figure 3. As can be seen in Figure 7, there is no consistent effect of orthographic context on the cumulative

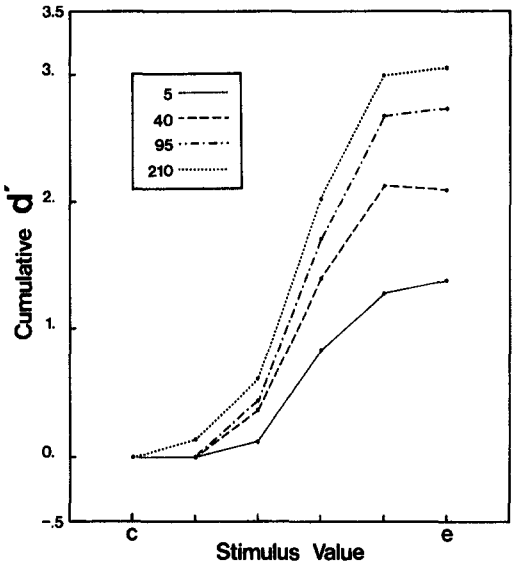

Figure 8. Cumulative d' values for the *e-c* letter set as a function of the stimulus value of the test letter and the interstimulus interval in msec.

d' values. These results indicate that the discrimination of bar length of the test letter did not change with context. The observed equivalence between both legal and both illegal contexts is direct evidence against nonindependence models. Subjects should have performed differently in both legal than in both illegal contexts, since these models assume that the context modifies lower level feature analyses and, therefore, the discriminability of bar length.

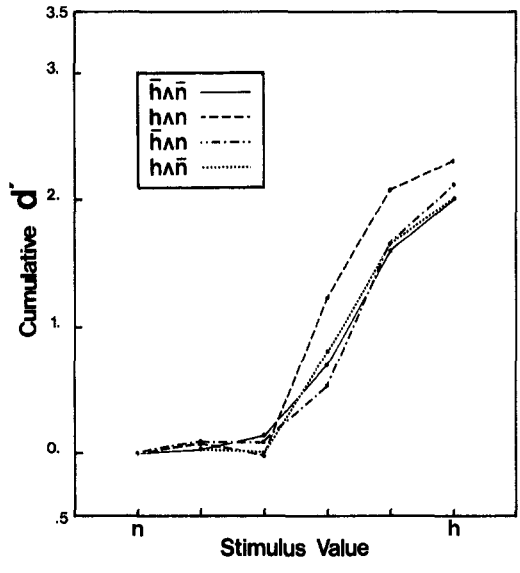

Figure 9. Cumulative d' values for the *h-n* letter set as a function of the stimulus value of the test letter and the orthographic context.

One might question whether the cumulative d' values would be sensitive to a context effect on visual resolution on the target letter. Evidence on this question can be derived from the effect of some other variable on the cumulative d' values. It is well-known that visual resolution improves with the processing time available for a test stimulus before the onset of a masking stimulus. Figure 8 gives the cumulative d' values for the *e-c* stimulus set plotted with ISI as the parameter. The values show a consistent and large effect of ISI. Discriminability as measured by cumulative d' values increased with increases in the available processing time. This result supports the assumption that the cumulative d' values are sensitive measures of the discriminability of the test letter. The fact that ISI and, therefore, processing time enhanced resolution of bar length shows that the failure to find an effect of orthographic context on discriminability cannot be due to an insensitive test. This conclusion will also be supported by the good description of the data by an independence model based on the assumption that discriminability of the bar length (V_i) is independent of context.

Figures 9 and 10 give the same analyses for the *h-n* stimulus set. In contrast to the *e-c* stimulus set, there is a hint of slightly larger cumulative d' values for the $h \wedge n$ context relative to the other three contexts. Given that the d' analysis was performed on response probabilities averaged across subjects, it is difficult to evaluate whether the observed difference is significant. The difference is relatively small, however, when compared to the large effect of ISI in Figure 10. Even if the small difference is real, however, it does not necessarily support the nonindependence class of theories, since differences in the visual characteristics of the context letters may be responsible. Given that the different contexts required different letters in the

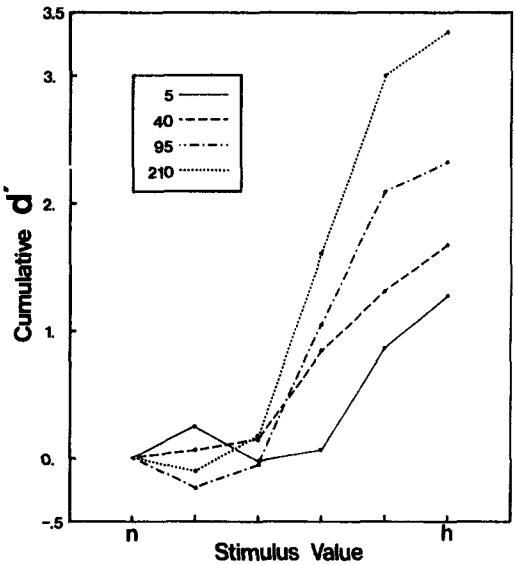

Figure 10. Cumulative d' values for the h-n letter set as a function of the stimulus value of the test letter and the interstimulus interval in msec.

test string, it was not possible to control exactly the contribution of lateral masking and feature similarity (Bjork & Murray, 1977; Estes, 1972).

Defining i, t, d, k, and l as having ascending verticals that might interfere with discrimination of the vertical bar of the test letter, one of these letters occurs in only one of the 4 test items of the $h \wedge n$ context, whereas at least one of these letters occurs in 10 of the 12 test items of the other three orthographic contexts. To assess whether the visual characteristics of the context letters may have been responsible for the advantage of the $h \wedge n$ context, the data were repartitioned according to whether or not the condition had any ascending verticals, and then a cumulative d' analysis was carried out. The average responses of the 5 conditions that had no ascending verticals gave a cumulative d' value of 2.36, whereas the average responses of the 11 conditions that had at least one ascending vertical gave a cumulative d' value of 1.87. This .49 difference is even larger than the .30 difference between the $h \wedge n$ and $\bar{h} \wedge \bar{n}$ contexts. This analysis supports the idea that any discrimination advantage with the $h \wedge n$ context is more likely to be due to the visual characteristics of the letters themselves than the fact that both letters are orthographically legal for $h \wedge n$.

Independence Model

The independence model provides a straightforward interpretation of the experimental situation. Two independent sources of information are available: the visual information from the critical letter and the orthographic context. These two sources are first evaluated independently and then integrated together before a decision operation determines which alternative provides the best match relative to the other possible alternatives under consideration. These three distinction operations are analogous to the three operations proposed by Oden and Massaro (1978) for the identification of speech sounds.

The visual information from the critical letter can be represented by V_i, where the subscript i indicates that V_i changes only with bar length. For the e-c identification, V_i specifies how much e-ness is given by the critical letter. This value lies between zero and one and is expected to increase as the length of the bar is increased. With the two contrasting alternatives e and c, it is reasonable to assume that the amount of c-ness given by the visual information is simply one minus the amount of e-ness given by that same source. Therefore, if V_i specifies the amount of e-ness given by the test letter, then $(1 - V_i)$ specifies the amount of c-ness given by that same test letter.

The orthographic context provides independent evidence for e and c. The value C_j represents how much the context supports the letter e. The subscript j indicates that C_j changes only with changes in orthographic context. The value of C_j lies between zero and one and should be large when e is legal and small when e is illegal. The degree to which the orthographic context supports the letter c is indexed by D_j and is independent of the value of C_j. The value of D_j also lies

between zero and one and should be large when c is legal and small when c is illegal.

The reader is assumed to have two independent sources of information. At the evaluation stage, the reader evaluates the amount of e-ness and c-ness from these two sources. The integration operation combines the two sources to arrive at values of e-ness and c-ness. The e-ness and c-ness values for a given test display can therefore be represented by the conjunction of the two independent sources of information:

$$e\text{-ness} = (V_i \Lambda C_j) \quad (1)$$

$$c\text{-ness} = [(1 - V_i)\Lambda(D_j)]. \quad (2)$$

It is now necessary to define conjunction in the model so that the e-ness and c-ness values given by both sources can be determined. Research in other domains has shown that a multiplicative combination provides a much better description than an additive combination (Massaro & Cohen, 1976; Oden, 1977; Oden & Massaro, 1978). If the multiplicative combination is applied here, Equations 1 and 2 can be represented as Equations 3 and 4, respectively:

$$e\text{-ness} = V_i \times C_j \quad (3)$$

$$c\text{-ness} = (1 - V_i) \times (D_j). \quad (4)$$

Finally, the decision operation determines which alternative provides the best response choice based on the e-ness and c-ness values. Again, following work in other domains, a choice of e is assumed to be made by evaluating the degree of e-ness relative to the sum of e-ness and c-ness values. This choice rule is a direct application of Luce's (1959) choice axiom. In this case the probability of an e response, $P(e)$, can be expressed as

$$P(e) = \frac{V_i C_j}{V_i C_j + (1 - V_i)(D_j)}. \quad (5)$$

Now it is necessary to derive $P(e)$ for the four orthographic contexts in the present experiment. A simplifying assumption about context is that a given alternative is supported to the degree x by a legal context and to the degree y by an illegal context, where $1 \geq x > y \geq 0$. The values x and y do not have subscripts, since they depend only on the legality of the context. Therefore, C_j is equal to x when e is legal in a particular context and equal to y when e is illegal. Analogously, D_j is equal to x when c is legal in a particular context and equal to y when c is illegal.

$$(e \Lambda \bar{c}): P(e) = \frac{V_i x}{V_i x + (1 - V_i)y}, \quad (6)$$

since the e-ness is given by $V_i x$ and the c-ness by $(1 - V_i)y$. Similar expressions can be derived for the other three contexts.

$$(e \Lambda c): P(e) = \frac{V_i x}{V_i x + (1 - V_i)x} = V_i \quad (7)$$

$$(\bar{e} \Lambda \bar{c}): P(e) = \frac{V_i y}{V_i y + (1 - V_i)y} = V_i \quad (8)$$

$$(\bar{e} \Lambda c): P(e) = \frac{V_i y}{V_i y + (1 - V_i)x}. \quad (9)$$

Equations 6 and 9 predict an effect of context to the extent that a legal context gives more evidence for a particular test letter than does an illegal context (i.e., to the extent that $x > y$). A second feature of this model is that $P(e)$ is entirely determined by the visual information when the context supports either both or neither of the test alternatives; Equations 7 and 8 both predict $P(e) = V_i$.

This form of the independence model was tested against the observed response probabilities averaged across subjects, letter position, and ISI. Figure 3 gives the observed and predicted values for the e-c stimulus set. To fit the model to the data, it was necessary to estimate six values of V_i for each level of bar length of the critical letter, an x value for the legal context, and a y value for the illegal context. The parameter values were estimated using the iterative routine STEPIT by minimizing the squared deviations between predicted and observed probability values (Chandler, 1969).

The model provides a relatively good description of the results. In addition, the parameter estimates appear to be psychologically meaningful. The value of V_i increased with increases in the length

of the bar of the critical letter. The values were .11, .11, .19, .60, .85, and .86 for the six respective levels. The value of x was .76 for legal context, and the value of y was .40 for the illegal context. The root mean squared deviation between the predicted and observed response probabilities was .02. It is clear that an additive combination of the two sources would fail, since the curves would have to be parallel. Supporting this, the root mean squared deviation was 2.5 times larger for a model based on an additive combination of the independent sources.

The theoretical description of the *h-n* data set is given in Figure 5. The values of V_i, the visual information supporting *h*, increased with increases in the length of the vertical bar. The values were .20, .21, .21, .51, .82, and .90 for the six respective levels. The value of x was .99 for the legal context and .44 for the illegal context. The root mean squared deviation was .04, about twice as poor as it was for the *e-c* data set but about two times better than an additive combination of the two sources of information. In summary, both the *e-c* and *h-n* results can be described reasonably well by an independence model assuming a multiplicative combination of the two sources of information.

Related Work

The present model shares some similarities with the theory proposed by Estes (1975a, 1975b). In common with the present model, a basic assumption of the Estes theory is that feature extraction of an input proceeds independently of the orthographic properties of surrounding context letters. Furthermore, orthographic context can influence how likely a degraded input (one without complete featural information) will be accepted as a particular letter. If adjacent letters are compatible with a particular letter, the degraded input will be more likely to be interpreted as that letter than if the adjacent letters are incompatible with that letter. Both models describe letter processing in terms of the independent contributions of featural information and orthographic context.

The Estes model also differs from the current model in that it allows orthographic context to provide auxiliary information regarding letter positions and to increase the likelihood that the response will be based on the stimulus input from the target location. Well-structured orthographic context reduces uncertainty about the location of the target letter. Consider the case in which the target letter is presented in final position in the *e-c* stimulus set. In the orthographic context tal__, it would be easier to locate the test letter in the final position rather than in penultimate position, since *tale* and *talc* are legal patterns, whereas *tael* and *tacl* are illegal patterns. In an illegal context, the target letter might be located in either final or penultimate position, since *tlae* and *tlac* are not much more appropriate than *tlea* and *tlca*. According to the Estes model, readers should make their decisions on the basis of the input information of the correct letter more often in the both legal than in the both illegal context. This assumption places the Estes model in the class of nonindependence models, since it predicts that context will modify how much information the reader transmits about the test letters. Therefore, the equivalent results in both legal and both illegal contexts can be interpreted as evidence against the Estes model.

The present results and theoretical description are consistent with recent findings of Krueger and Shapiro (1979) Subjects monitored lists of items presented one item at a time at varying rates of presentation. The lists of items were composed of six-letter words or six-letter nonwords. In one experiment, subjects indicated whether a mutilated *A* or a mutilated *E* appeared in a list of words or nonwords. Recognition performance was higher for word than for nonword lists. In terms of the present analysis, the orthographic constraints of the letters in words supplemented visual information passed on feature analysis and allowed better resolution of whether a mutilated letter was an *A* or an *E*.

In another similar experiment, subjects

had to indicate whether or not a mutilated *A* was present in a list of words or nonwords. No performance differences were found as a function of orthographic context. This result indicates that detection of a mutilation was not modified by orthographic context, in agreement with the assumption that orthographic context does not modify feature analysis. That is to say, detection of a mutilation could be performed independently of letter recognition, and, therefore, orthographic context had no effect. When subjects have to recognize whether a mutilated letter was an *A* or *E*, however, orthographic context could supplement feature analysis in the recognition of the critical letter and, therefore, improve performance in the recognition task. Krueger and Shapiro's results support the idea that orthographic context enhances letter perception by providing an independent source of evidence rather than by modifying feature analysis.

A Final Note

A potential criticism from the nonindependence theorist is that the present task produced a letter rather than a word recognition strategy. Given the letter strategy, orthographic context could not be expected to influence visual feature analysis (Johnston & McClelland, 1974). Although this interpretation would allow the equivalence of the $(e \wedge c)$ and $(\bar{e} \wedge \bar{c})$ contexts, it cannot account for the large effect of orthographic context in the $(\bar{e} \wedge c)$ and $(e \wedge \bar{c})$ test items. Given the positive effects of bar length, orthographic context, and processing time (ISI), the present experiment appears to be completely representative of the class of experiments currently being carried out in letter and word perception (e.g., McClelland, 1976; Krueger & Shapiro, 1979). The results, therefore, provide strong support for the idea that orthographic structure and visual feature information provide independent sources of information in word perception. Any assumption of orthographic context overriding and changing the nature of feature analysis is unwarranted.

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Received September 8, 1978 ■