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Disruption to Word or Letter Processing? The Origins of Case-Mixing Effects

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MiXeD-cAsE stimuli have long been used to test whether word recognition is based on holistic visual information or preliminary letter identification. However, without knowing which properties of mixed-case stimuli disrupt processing, it is not possible to determine which visual units mediate word recognition. The present studies examined the effects of case mixing on word and nonword naming as a function of (a) whether spaces were inserted between letters and (b) whether letter size was alternated independent of letter case. The results suggest that case-mixing disruption effects are due to at least 2 factors: the introduction of inappropriate grouping between letters with the same size and case, and the disruption of transletter features. The data support a model of visual lexical access based on the input from multiple visually based units.

Experiments involving MiXeD-cAsE stimuli have long been used by researchers to examine whether word recognition is based on holistic visual information or on prior letter identification. Although studies have suggested that people can switch between different forms of case mixing with relative ease when reading text (McConkie & Zola, 1979; Rayner, McConkie, & Zola, 1980), case mixing itself disrupts reading performance relative to when all of a word's letters are presented in lower- or uppercase. However, the cause of this robust effect remains unclear. Most accounts of case-mixing disruption effects agree that disruption takes place early in the word recognition system when visual features are encoded (Besner & McCann, 1987; Mayall & Humphreys, 1996; Mewhort & Johns, 1988), though the precise features that are affected are still unknown. Besner (1989) provided some evidence suggesting that the effect of case mixing is not caused by the disruption of word shape. Common function words, which are often assumed to be recognized through their word-specific visual patterns, were no more affected by case mixing in naming and lexical-decision tasks than were other control words. Other possible causes of the case-mixing disruption effect include lateral masking of smaller by larger letters, the disruption of perceptual units that span one or more letters (transletter features), or the inappropriate grouping of letters in the same case.

The effects of case mixing have been studied with a number of tasks: letter identification (Adams, 1979; Besner, 1989; McClelland, 1976; Mewhort & Johns, 1988), word and nonword naming (Besner & Johnston, 1989; Mayall & Humphreys, 1996), lexical decision (Besner & McCann, 1987; Mayall & Humphreys, 1996), semantic categorization (Mayall & Humphreys, 1996), and syntactic categorization (Kinoshita, 1987). In all tasks, case mixing disrupts performance, although the size of the disruption depends on the type of stimuli. For instance, in naming, reaction times (RTs) to low-frequency words are more affected by case mixing than those to high-frequency words (Besner, Davelaar, Alcott, & Parry, 1984; Besner & McCann, 1987; Mayall & Humphreys, 1996). RTs to nonwords, at the extreme of the frequency continuum, are affected even more strongly than RTs to low-frequency words (Besner & Johnston, 1989; Mayall & Humphreys, 1996).

On the Visual Information Disrupted by Case Mixing

Although the above studies all showed strong effects of case mixing on performance (e.g., those reported by Mayall & Humphreys, 1996, range from 36 ms to 146 ms compared with lowercase items, depending on task and word type), they do not address the question of what kinds of visual information are disrupted by case mixing; hence, they do not allow conclusions to be made about the nature of the visual units mediating word recognition. There are several possible explanations as to why case mixing affects word processing. First, it may be that word shape is an important factor for word identification, and familiar word shape is disrupted by presenting stimuli in mixed case. However, a proofreading task presented by Paap, Newsome, and Noel (1984), in addition to the results of Besner (1989) that we have already discussed, provided evidence that calls this into question. In Paap et al.'s study, spelling errors were created by substituting a single letter within a word. The substitute letters either maintained or altered the shape of the word and were either confusable with or distinctive from the original. For example, the word *than* became *tban* (maintained shape, confusable), *tdan* (maintained shape, distinctive), *tnan* (altered shape, confusable), or *tman* (altered shape, distinctive). Significantly more errors were missed in proofreading the

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text when the substitute letter was confusable with the original, but no effect of altering or maintaining word shape was found. In other studies, case mixing has been shown to disrupt nonword naming to a greater extent than word naming (Besner & Johnston, 1989; Mayall & Humphreys, 1996). If word shape is important in naming, word naming should have been more disrupted by case mixing than nonword naming.

A second possible cause of case-mixing effects is the disruption of transletter features (Besner & Johnston, 1989; Mewhort & Johns, 1988). These features, larger than single letters but smaller than whole words, may be used in normal word recognition but are disrupted by case mixing. Examples of transletter-feature disruption by case mixing, provided by Besner and Johnston (1989), include the following: the insertion of entirely different letter features (e.g., *e* vs. *E*), the introduction of differing relative sizes of letters, and the distortion of the shape of the spaces between letters (Wheeler, 1970).

Third, single-letter identification may be adversely affected by case mixing. For instance, there is a possibility of lateral masking from uppercase to lowercase letters within the letter strings (Besner & Johnston, 1989). However, Coltheart and Freeman (1974) showed that the recognition of mixed case words was still inferior to that of normal case words when upper- and lowercase letters were of the same size (e.g., gArDeNeR). When presented with words in lowercase, uppercase, or mixed case for 50 ms, participants made more incorrect responses and omissions for mixed-case words. As letters were of the same size in this manipulation, masking of smaller by larger letters could not have been the cause of the effect. This suggests that case-mixing disruption effects with the usual case manipulation (e.g., gArDeNeR) cannot be caused solely by masking from larger onto smaller letters; another factor must also have an effect. However, because Coltheart and Freeman did not include conditions with "standard" mixed-case stimuli, the relative magnitude of any disruption due to the letters being different sizes cannot be deduced.

One further possible cause of case-mixing disruption effects is the inappropriate grouping of same-case letters. For instance, the *A* and *E* in the word *ArEa* may be grouped together and may form an inappropriate unit for visual lexical access, slowing recognition. This is examined in Experiment 3 here.

Smith and his colleagues (Smith, 1969; Smith, Lott, & Cronnell, 1969) studied the effects of several manipulations of letter case and size on two tasks. Participants were presented with text printed in lowercase, uppercase, alternating case of the same size (e.g., iGnOrAnT), alternating-size uppercase letters (e.g., IGNORANT), alternating-size lowercase letters (e.g., ignorant), and letters alternating in both case and size (e.g., IgNoRaNt). When asked to read the passage of text aloud, participants were slower in two conditions: alternating-size lowercase and alternating size and case. When participants were asked to find particular words within the text, the conditions in which letter size was alternated were all slower than those in which letter size remained consistent. Smith (1969) argued that words are identified on the basis of distinctive features, including, for instance, the curvature and intersection of letter features, the relative size of letters, and the presence or absence of ascenders and descenders. He explained his results by suggesting that alternating the size of letters makes it more difficult to discriminate between the features, as relative size is an important cue. However, the results could also be explained by lateral masking or incorrect grouping of the larger letters. Moreover, the tasks used by Smith were not ideal to study word recognition per se, as context effects from the texts could have played an important part in the time taken to complete the tasks. In Experiment 3 here, the factors of case mixing and relative size of letters within the string were manipulated orthogonally in a single word-naming task, to enable more definite conclusions to be drawn concerning the relative effects of the two variables on word recognition.

In summary, there are several possible causes of case-mixing disruption effects that could potentially be contributory factors or even the sole cause of the effect. These include the following: (a) disruption to word shape or to transletter features, (b) lateral masking of lowercase letters by the larger uppercase letters, and (c) the inappropriate grouping of same-case letters. The three experiments described in this article investigated which of the possible causes described above is responsible for case-mixing disruption effects on reading individual words. Experiments 1 and 2 examined changes in performance when spaces were inserted between lowercase and mixed-case letters. Experiment 3 investigated the consequences of separating out the letter size and case alternation variables, by presenting stimuli in alternating-size lowercase letters (e.g., hearing) and in mixed case in which lower- and uppercase letters were of the same size (e.g., HeArInG), in addition to standard- and mixed-case conditions.

The naming of words and nonwords was blocked in Experiments 2 and 3, because we wanted to avoid the possibility that mixing words and nonwords could cause a nonlexical naming strategy to be used on the words (see Baluch & Besner, 1991; Colombo & Tabossi, 1992; Monsell, Patterson, Graham, Hughes, & Milroy, 1992; Tabossi & Laghi, 1992; but also see Lupker, Brown, & Colombo, 1997). As a consequence, in Experiment 2, nonword naming always followed word naming (so word naming was not affected by prior nonword naming), and in Experiment 3, an analysis of block-order effects on word naming was conducted as described.

Experiment 1: Case and Spacing Effects on Word Naming

Campbell, Mewhort, and Marchetti (Campbell, 1985; Campbell & Mewhort, 1980; Mewhort, Marchetti, & Campbell, 1982) have investigated the effects of adding spaces to strings of uppercase letters on various tasks. In tasks requiring free recall of an eight-letter pseudoword or requiring recall of a single letter from the string probed by a digit (corresponding to the letter's position within the string), performance was typically better if letter strings had an orthographic structure that approximated to English. This facilitatory effect of approximation to English was reduced by letter spacing (Campbell & Mewhort, 1980). This suggests that when letters are spaced, stimuli have to be processed more as strings of letters than as wordlike wholes. It follows that the processing of letters as wordlike wholes depends on the coding of visual units above the letter level. It is interesting that the relative size of spaces compared to letters, rather than simply an increase in the visual angle of the stimulus, is crucial to this effect (Mewhort et al., 1982). Thus, the facilitatory effect of greater orthographic regularity is reinstated if the spaces are maintained but letter size is increased.

Campbell (1985) compared letter-spacing effects, also on eight-letter strings, using both a simultaneous- and a successive-matching task. The two stimuli on each trial were pseudowords presented in uppercase (e.g., *HEMINDOL*), and in the "different" condition, the second stimulus had one letter different from the first. Campbell found that letter spacing reduced RTs in the simultaneous-matching task, whereas it increased RTs in the successive-matching task. This suggests a difference between the strategies used in the two tasks. In the successive-matching task, the first string of letters needs to be held in memory, so the more wordlike the string is, the smaller the number of "chunks" to be maintained is and the easier the task is. Spacing the letters makes them harder to chunk together and therefore harder to hold in memory. In the simultaneous-matching task, individual letters are likely to be compared between the two strings. Therefore, any reduction in lateral masking (e.g., by letter spacing) is advantageous.

Experiment 1 here examined the effect on word naming of spacing the constituent letters of words typed in both lowercase and mixed case. Table 1 presents predictions from the various theories of case mixing described above. Disruption to word shape is not included because, first, it can be seen as a special case of disruption to transletter features and, second, previous studies suggest that word shape is little used in word recognition (see the introduction). One other factor concerns the loss of acuity, which should decrease performance with spaced letters. However, this loss should have the same effect on lowercase and mixed-case stimuli, so no differential effects of spacing were expected. Table 1 then provides predictions from the transletter-feature theory, the masking theory, and the inappropriate-letter-grouping theory of case mixing. The transletter-feature theory predicts that letter spacing should disrupt naming of lowercase words, while having no effect on mixed-case words. Both the masking and the letter-grouping theories predict that letter spacing should have no effect on the naming of lowercase words, while facilitating the naming of mixed-case words.

Method

Participants. Sixteen undergraduate students from the University of Birmingham, England, with normal or corrected-to-normal vision took part in this experiment. Participants were paid £1.50.

Stimuli. Stimuli consisted of 144 words all three to six letters long with a mean length of 4.47 letters and a standard deviation of 0.73 letters. The mean Kučera and Francis (1967) frequency of words was 397.6, and the standard deviation was 966.0. The average mean bigram frequency of the words was 66.92 per 20,000 words, with a standard deviation of 47.58. Stimuli were typed in Turbo Pascal sans serif and subtended a visual angle of 1.0°–3.8° depending on length and spacing. Letters and spaces were approximately 3 mm wide, and the viewing distance was 50 cm. Half of the words were presented in mixed case and half in lowercase. Mixed-case words consisted of alternating lower- and uppercase letters. Half of the mixed-case words had an initial lowercase letter, and half had an initial uppercase letter. For each case manipulation, half of the words were presented with a space between each letter (e.g., *s E n S e*). The case and letter-spacing manipulations for each stimulus were balanced across subjects, so that each item appeared equally often in each Case × Spacing format. Word frequency and spelling-to-sound regularity were balanced across conditions for a given participant.

Procedure. Stimuli were presented in random order in the center of a Samsung 10" monochrome monitor serving an Elonex PC 386SX-160. The luminance of the display was 23–33 cd/m^2 depending on the length of words. Participants were asked to read the words as quickly as possible without making errors. Items remained on the screen until a response was made. Participants responded by speaking the word into a microphone connected to a voice key.

Results and Discussion

Mean correct RTs and the percentage of answers that were errors can be seen in Table 2, and the size of effects can be seen in Table 3. Analyses of variance (ANOVAs) were

Table 1
Predictions for Experiment 1 From Theories of Case Mixing

Hypothesis	Prediction
1. Disruption of transletter features	A. Spacing lowercase letters will increase reaction times (RTs). B. Spacing mixed-case letters will have no additional effect.[a]
2. Masking of lowercase letters	A. Spacing mixed-case letters will reduce RTs.[b] B. Spacing will have no effect on lowercase words.
3. Inappropriate letter grouping	A. Spacing mixed-case letters will reduce RTs.[b] B. Spacing will have no effect on lowercase words.

[a]The prediction follows because transletter features are already disrupted in mixed-case words. [b]These predictions follow because spacing will reduce the possibility of lateral masking and inappropriate letter grouping.

calculated across both subjects and items[1] and are reported in Table 4. It can be seen from Table 4 that there were significant effects of case mixing and spacing and a significant interaction. (A significance level of $p < .05$ was used throughout this study.) There was overall a 48-ms advantage for lowercase words over mixed-case words, and a 20-ms advantage for words with spaced letters compared to those with unspaced letters. The effect of spacing was larger on mixed-case words. A Newman–Keuls test on the data across subjects indicated that there was a significant facilitatory effect of spacing on mixed-case words, but no spacing effect on lowercase words.[2] Increases in the number of errors corresponded with increases in RTs (see Table 2): There was no evidence of a speed–accuracy trade-off, and so these data were not subjected to further analysis.

The results support Theories 2 and 3 from Table 1, because spacing facilitated performance with mixed-case words while having no real effect on lowercase words. This suggests that case-mixing disruption effects may be caused by the masking of lowercase letters by the larger uppercase letters or by the inappropriate grouping of same-case letters, but the disruption of transletter features seems an unlikely cause of the effects. However, as there is a 30-ms case-mixing effect even with spaced words, it is possible either that (a) there is a further contributory factor to the case-mixing effect which is not reduced by letter spacing, or (b) the manipulation of letter spacing was not strong enough to eliminate lateral masking or inappropriate letter grouping completely.

The fact that spacing has little effect on the naming of lowercase words suggests that neither the loss of transletter feature information nor decreases in acuity affected performance with the current stimuli. This result appears to contradict the data of Campbell and Mewhort (1980), where effects of approximation to English were reduced by letter spacing. There are several possible reasons for this difference. First, Campbell and Mewhort used uppercase letters, whereas we used lowercase. Possibly, lowercase stimuli, having more individualistic word shapes and being encountered more frequently, can be better perceived as wholes even when letter spacing is introduced. Second, we used real words and Campbell and Mewhort's experiment involved pseudowords. The letters in a real word may again be easier to group, because of familiarity, contact with lexical knowledge, or both; again, words may hold up better under conditions of letter spacing. Third, the stimuli used by Campbell and Mewhort were all eight letters in length, whereas the stimuli used here were three to six letters in length. Because our stimuli were shorter, it is less likely that problems were caused by letters being presented in peripheral retinal positions. The net result is reduced effects of spacing on performance in our experiment compared with the effects found by Campbell and Mewhort.

Table 2
Mean Reaction Times (RTs; in Milliseconds) and Errors (in Percentages) in Word Naming in Experiment 1

Spacing and case	RT	Spoiled trials (%)	Error (%)
Unspaced			
Lowercase	502	4.7	2.0
Mixed	567	2.1	2.8
Spaced			
Lowercase	499	2.8	2.3
Mixed	529	5.0	2.7

Note. Spoiled trials were trials in which the voice key was activated accidentally or was not activated by the response. RT = reaction time.

Table 3
Effects (in Milliseconds) of Spacing and Case Mixing on Word Naming in Experiment 1

Variable	Effect (ms)
Spacing	
Lowercase	3
Mixed case	38
Case	
Unspaced	−65
Spaced	−30
Spacing × Case	35

Experiment 2: Case-Mixing and Letter-Spacing Effects on Word Versus Nonword Naming

It has previously been shown that the effect of case mixing on nonword naming is greater than the effect on word naming (Besner & Johnston, 1989; Mayall & Humphreys, 1996). Mayall and Humphreys (1996) explained this by suggesting that the initial visual encoding of a letter string is facilitated by top-down lexical information. An alternative explanation is that case mixing disrupts nonlexical naming to a greater extent than lexical naming (see Besner, 1990). However, this was rejected by Mayall and Humphreys because, in their study, there was a greater case-mixing disruption effect on naming when it appeared to have been lexically mediated (because of the inclusion of irregular words in the experiment), than when it was likely to have been nonlexically mediated (because of the inclusion of nonwords).

In Experiment 2 here, we considered the effects of letter spacing on the naming of mixed-case words and nonwords. Table 5 provides predictions for the experiment from two of the theories of case mixing. The disruption-of-transletter-

[1] Individual naming latencies more than 2.5 *SD*s from the mean for a particular participant in a particular condition were removed before analyses were made. In all items analyses considered here, any points of missing data were filled by entering the means across other occurrences of the same item. Significance levels were unchanged if means across items in the same condition were used.

[2] A study of median RTs replicated the analysis of the mean data. There was a significant effect of spacing on mixed-case words—unspaced, 560 ms; spaced, 513 ms; $t(16) = 2$—but there was no effect of spacing on lowercase words—unspaced, 496 ms; spaced, 486 ms; $t(16) = 63$. This suggests that there is no substantial difference in the shape of RT distributions for lowercase spaced and unspaced words that is being hidden by the use of means.

Table 4
Analysis of Variance for Experiment 1

Subjects analysis			Items analysis		
Source	*df*	*F*	Source	*df*	*F*
Case (C)	1	30.18***	C	1	34.29***
C × *S* within-group error	15	(1,163.30)	C × *S* within-group error	143	(11,799.99)
Spacing (S)	1	9.82**	S	1	16.58***
S × *S* within-group error	15	(675.18)	S × *S* within-group error	143	(4,748.16)
C × S	1	11.56**	C × S	1	14.45***
C × S × *S* within-group error	15	(414.91)	C × S within-group error	143	(3,564.54)

Note. Values enclosed in parentheses represent mean square errors. *S* = subjects.
$^{**}p < .01$. $^{***}p < .001$.

features theory is excluded because Experiment 1 provided evidence against this.

Predictions from the letter-grouping theory are not easy to make. It is not obvious why inappropriate letter grouping should have differential effects on word and nonword naming; therefore, the prediction is made that the effect should be of the same size. Similarly, for this account, spacing should reduce the case-mixing disruption effect to the same extent for words and nonwords. In contrast, if there is masking of letters in mixed-case stimuli, nonword naming should be more disrupted than word naming, because the identification of individual letters should be more important for nonwords than for words. Following this prediction, spacing should reduce the larger case-mixing disruption effect for nonwords more than it reduces the smaller case-mixing disruption effect for words.

Method

Participants. Twenty-four undergraduate students from the University of Birmingham, England, with normal or corrected-to-normal vision participated in this experiment. They were either paid to take part in this and other (unrelated) experiments or were psychology undergraduates taking part in a research participation scheme to earn course credits.

Stimuli. Stimuli consisted of 120 words and 80 nonwords all four to six letters long (those used by Mayall & Humphreys, 1996, Experiment 1). Words had a mean length of 4.95 letters and a standard deviation of 0.83 letters. They had a mean bigram frequency of 50.23 per 20,000 words, with a standard deviation of 39.07. Nonwords had a mean length of 4.99 letters and a standard deviation of 0.74. They had a mean bigram frequency of 39.76 and a standard deviation of 32.17. This was significantly lower than that for words, $t(189) = 2.07$. Words had a mean Kučera and Francis (1967) word frequency of 130.3, with a standard deviation of 227.7. Nonwords were all pronounceable and were made from real words with a single letter replaced. Stimuli were typed in Turbo Pascal sans serif and subtended a visual angle of 1.4°–3.8°, depending on length and spacing. Letters and spaces were approximately 3 mm wide, and the viewing distance was 50 cm. Forty stimuli were presented to each participant in both a word-naming and a nonword-naming task. Participants were presented with half of the stimuli in mixed case and half in lowercase. Of these, half had spaces between letters and half did not. Items were matched for word frequency across the case and spacing manipulations, and each item appeared equally often in each Case × Spacing format.

Procedure. Participants were presented with a word-naming task followed by a nonword-naming task. The nonword-naming task was always presented after the word-naming task, so that the naming of nonwords did not influence how participants named words. In both tasks, presentation of stimuli and responses were as in Experiment 1. Items were presented in random order within the tasks, and the stimulus sets were balanced across subjects.

Results and Discussion

Mean RTs and the percentage of answers that were errors can be seen in top half of Table 6, and the size of effects can be seen in Table 7. Results from ANOVAs across subjects and across items can be seen in Table 8.

In this experiment, there was a 196-ms overall advantage for the naming of words over nonwords, an overall 59-ms advantage for lowercase stimuli over mixed-case stimuli, and an overall 15-ms advantage for spaced items over unspaced items. Case mixing had a 32-ms effect on word naming and an 86-ms effect on nonword naming. A Newman–

Table 5
Predictions for Experiment 2 From Theories of Case Mixing

Hypothesis	Prediction
1. Masking of lowercase letters	A. Case-mixing disruption effects will be greater on nonword naming than on word naming.[a] B. Spacing will reduce the case-disruption effect more for nonwords than for words (i.e., there will be a larger Spacing × Case interaction for nonwords than for words).
2. Inappropriate letter grouping	A. Case-mixing disruption effects on word and nonword naming will be equivalent. B. Spacing will reduce the case-mixing disruption effect to the same extent in word and nonword naming (i.e., the Spacing × Case interaction will be equivalent for word and nonword naming).

[a]The prediction follows because analysis of individual letters is more important in nonword naming.

Table 6
Mean Reaction Times (RTs; in Milliseconds) and Errors (in Percentages) in Word Naming and Nonword Naming in Experiments 2 and 3

	Word naming			Nonword naming		
Spacing and case	RT	Spoiled trials (%)	Error (%)	RT	Spoiled trials (%)	Error (%)
			Experiment 2			
Unspaced						
Lowercase	510	2.5	1.3	685	3.3	4.3
Mixed	560	2.5	3.0	789	2.9	7.7
Spaced						
Lowercase	520	3.3	0.4	682	3.3	3.0
Mixed	534	2.9	2.6	751	2.9	3.9
			Experiment 3			
Unspaced						
Lowercase	509	4.5	1.0	744	6.0	1.9
Mixed	587	4.1	4.7	899	8.4	4.3
Spaced						
Lowercase	521	4.5	0.9	782	6.6	1.8
Mixed	568	4.9	4.5	896	5.6	4.2

Note. Spoiled trials were trials in which the voice key was activated accidentally or was not activated by the response.

Keuls test on the Word–Nonword × Case interaction showed that case-mixing disruption effects were significant on both words and nonwords, though the reliable interaction indicates that the case-mixing effects were larger on nonwords. This replicates the findings of Besner and Johnston (1989) and Mayall and Humphreys (1996), and therefore is unlikely to have been due to the nonword-naming task always following the word-naming task. As noted in the introduction, this finding is incongruent with the hypothesis that case mixing affects performance by breaking up overall word shape. It supports the lateral-masking hypothesis, but not the inappropriate-letter-grouping hypothesis (see Table 5).

As in Experiment 1, spacing had a facilitatory effect on the naming of mixed-case stimuli, but had no real effect on the naming of lowercase stimuli (see Table 7). A Newman–Keuls test showed that spacing the letters in mixed-case stimuli significantly facilitated naming, but there was no significant effect of spacing on lowercase stimuli. This finding is congruent with both the masking hypothesis and the inappropriate-letter-grouping hypothesis.

Third, for words and nonwords, there was an equivalent reduction in the case-mixing disruption effect when the letters of stimuli were spaced (35 ms vs. 36 ms for nonwords and words, respectively). The combined effects of case mixing and spacing did not interact significantly with the word–nonword factor. This supports the inappropriate-letter-grouping hypothesis, but not the lateral-masking hypothesis.

Considering the predictions made for this experiment in Table 5, the results do not provide full support for either theory. Nonword naming is more disrupted by case mixing than word naming, as is predicted by the lateral-masking hypothesis but not by the inappropriate-letter-grouping hypothesis. However, spacing reduces the case-mixing disruption effect on words and nonwords to the same extent, as predicted by the inappropriate-letter-grouping hypothesis but not by the masking hypothesis. This suggests that neither theory provides a full explanation for the disruptive effect of case mixing on naming. Mayall and Humphreys (1996) suggested that the differential case-mixing effect on word and nonword naming is caused by top-down lexical facilitation of word encoding. This would not be expected to interact with letter spacing. If this is so, there is no need to reject the inappropriate-letter-grouping theory of case-mixing disruption effects at this juncture. Both word and nonword reading could be disrupted by inappropriate letter grouping, but words benefit to some degree from top-down feedback.

In Experiment 3, we studied the effects of alternating letter size and case independently. This should separate out the masking and letter-grouping hypotheses, which provide different predictions for this experiment.

Table 7
Effects (in Milliseconds) of Spacing and Case Mixing on Word and Nonword Naming in Experiment 2

Variable	Word naming effect (ms)	Nonword naming effect (ms)
Spacing		
Lowercase	−10	3
Mixed case	26	38
Case		
Unspaced	−50	−104
Spaced	−14	−69
Spacing × Case	36	35

Experiment 3: Letter-Size, Case-Mixing, and Spacing Effects on Word and Nonword Naming

In this experiment, effects of letter size and case were manipulated orthogonally, and the effects of letter spacing were again examined. This resulted in four types of stimuli

Table 8
Analysis of Variance for Experiment 2

Subjects analysis			Items analysis		
Source	*df*	*F*	Source	*df*	*F*
Word–nonword (W)	1	96.33***	Between items		
W × *S* within-group error	23	(19,071.70)	W	1	296.28***
Case (C)	1	50.63***	*S* within-group error	198	(24,630.98)
C × *S* within-group error	23	(3,331.86)	Within items		
Spacing (S)	1	4.79*	C	1	51.35***
S × *S* within-group error	23	(2,135.83)	W × C	1	8.81**
W × C	1	9.32**	C × *S* within-group error	198	(15,054.67)
W × C × *S* within-group error	23	(3,716.67)	S	1	4.21*
W × S	1	1.30	W × S	1	0.76
W × S × *S* within-group error	23	(1,450.75)	S × *S* within-group error	198	(8,898.54)
C × S	1	6.45*	C × S	1	4.51*
C × S × *S* within-group error	23	(2,279.64)	W × C × S	1	0.03
W × C × S	2	0	C × S × *S* within-group error	198	(10,821.65)
W × C × S × *S* within-group error	23	(3,407.77)			

Note. Values enclosed in parentheses represent mean square errors. *S* = subjects.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

being presented with and without spaces: lowercase, consistent size (e.g., hearing); lowercase, alternating size (e.g., hearing); mixed case, consistent size (e.g., HEArInG), and mixed case, alternating size (e.g., HeArInG). In the standard case-mixing manipulation used in Experiments 1 and 2, case mixing and size mixing are confounded, and it is therefore not possible to determine how the two factors individually contribute to the standard case-mixing disruption effect. The predicted effects of the above manipulations from the masking and letter-grouping theories of case mixing are given in Table 9.

Method

Participants. Thirty-two students from the University of Birmingham, England, with normal or corrected-to-normal vision participated in this experiment. Participants were either paid to participate in this and other experiments or were psychology undergraduates taking part in the department's research participation scheme.

Stimuli. Stimuli consisted of 240 words and 240 nonwords. All words had a Kučera and Francis (1967) word frequency of 60 occurrences/million or more, with a mean of 302.1 and a standard deviation of 794.0. All words and nonwords were four to seven letters long and had a mean length of 5.18 letters and a standard deviation of 1.06 letters. Nonwords were all pronounceable and were the stimulus words with a single letter changed. Words had a mean bigram frequency of 67.99 per 20,000 words and a standard deviation of 70.79. Nonwords had a mean bigram frequency of 51.39 and a standard deviation of 57.11. This difference was statistically significant, $t(479) = 2.83$. Stimuli were typed in Turbo Pascal sans serif and subtended a visual angle of 6.9°–18.9°, depending on length and spacing. Letters and spaces were approximately 6 mm wide, and the viewing distance was 50 cm. Half of the stimuli were presented with spaces between the letters. For a given participant, one quarter of the words were presented in normal lowercase (e.g., hearing), and one quarter were presented in

Table 9
Predictions for Experiment 3 From Theories of Case Mixing

Hypothesis	Prediction
1. Masking of lowercase letters	A. There will be case-mixing disruption effect for stimuli with consistent-size letters.
	B. Size alternation will increase reaction times (RTs) independent of case.
	C. Spacing will reduce naming latencies for stimuli with alternating-size letters (by reducing masking).
	D. The disrupting effect of size alternation will be greater for nonwords than for words.
	E. The facilitatory effect of spacing size-alternated stimuli will also be greater for nonwords (i.e., the Spacing × Size alternation interaction will be greater for nonwords than for words).
2. Inappropriate letter grouping	A. If letter grouping is based on size, size alternation will increase RTs independent of case, and spacing will reduce the size-alternation effect (i.e., there will be a Spacing × Size Alternation interaction, equivalent for lowercase and mixed case).
	B. If letter grouping is based on case, case alternation will increase RTs independent of size, and spacing will reduce the case-alternation effect (i.e., there will be a Spacing × Case interaction, equivalent for consistent- and alternating-size stimuli).
	C. If letter grouping is based on case and size, the disruption from case and size alternation will be greater than the sum of the two individual effects (i.e., there will be an overadditive interaction of Size Alternation × Case), and only when case and size are both alternated will spacing reduce RTs.

normal mixed case (e.g., HeArInG; as in Experiments 1 and 2). The third quarter was presented in lowercase with alternating-size letters (e.g., hearing), and the fourth quarter was presented with alternate lower- and uppercase letters that were the same size (e.g., HeArInG). No letters that differed only in size between lower- and uppercase were used in this experiment. Each item appeared equally often in each Case × Spacing × Size format across subjects.

Procedure. Participants were given two tasks: word naming and nonword naming. The order of the tasks and the manipulation of the stimuli were balanced across subjects. The balancing of task order allowed us to evaluate the effect of naming nonwords before the naming of words. Items within the word and nonword sets appeared in random order and the methods of presentation and response were the same as in Experiment 1.

Results and Discussion

Mean RTs and the percentage of answers that were errors can be seen in Table 10, and the size of effects can be seen in Table 11. ANOVAs across both subjects (F_1) and items (F_2) were performed, and their results can be seen in Table 12.

Preliminary results. The results showed a 293-ms overall advantage for words over nonwords, a 54-ms overall advantage for lowercase over mixed-case stimuli, and an overall 45-ms advantage for stimuli with consistent letter sizes compared with stimuli with alternating letter sizes. Case mixing slowed word naming less than nonword naming (35 ms vs. 73 ms). When the data from words and nonwords were analyzed separately, both of these case-mixing effects reached significance: words, $F_1(1, 31) = 47.49$, $MSE = 1{,}637.52$; $F_2(1, 239) = 90.61$, $MSE = 7{,}946.00$; nonwords, $F_1(1, 31) = 33.69$, $MSE = 10{,}020.93$; $F_2(1, 239) = 59.86$, $MSE = 43{,}662.19$. Alternating the size of letters also had a greater disruptive effect on nonwords than words (62 ms vs. 27 ms), although again the effects on both stimulus types were significant when the data were analyzed separately: words, $F_1(1, 31) = 37.89$, $MSE = 1{,}275.00$; $F_2(1, 239) = 81.58$, $MSE = 5{,}632.35$; nonwords, $F_1(1, 31) = 24.99$, $MSE = 9{,}747.70$; $F_2(1, 239) = 80.37$, $MSE = 25{,}593.80$. For both words and nonwords, there were significant main effects of case mixing and letter-size variation, with the longest RTs being for the original type of mixed-case stimuli (e.g., HeArInG; see Table 10). Apparently, alternating both letter size and case affects processing. Finally, spacing had an overall 19-ms disruptive effect on consistent-size stimuli, while having a 5-ms facilitatory effect

Table 10
Mean Reaction Times (RTs; in Milliseconds) and Errors (in Percentages) in Word Naming and Nonword Naming in Experiment 3

Size, spacing, and case	RT	Spoiled trials (%)	Error (%)
Word naming			
Consistent			
Unspaced			
Lowercase	509	4.5	1.0
Mixed	545	5.1	1.9
Spaced			
Lowercase	521	4.5	0.9
Mixed	544	4.5	1.2
Alternating			
Unspaced			
Lowercase	534	4.5	1.5
Mixed	587	4.1	4.7
Spaced			
Lowercase	541	5.3	2.2
Mixed	568	4.9	4.5
Nonword naming			
Consistent			
Unspaced			
Lowercase	744	6.0	1.9
Mixed	836	6.4	2.3
Spaced			
Lowercase	782	6.6	1.8
Mixed	861	6.6	2.3
Alternating			
Unspaced			
Lowercase	840	7.4	2.6
Mixed	899	8.4	4.3
Spaced			
Lowercase	835	6.7	3.2
Mixed	896	5.6	4.2

Note. Spoiled trials were trials in which the voice key was activated accidentally or was not activated by the response.

Table 11
Effects (in Milliseconds) of Spacing, Size Alternation, and Case Mixing on Word and Nonword Naming in Experiment 3

Variable	Word naming effect (ms)	Nonword naming effect (ms)
Spacing (S)		
Consistent size		
Lowercase	−12	−38
Mixed case	1	−25
Alternating size		
Lowercase	−7	5
Mixed case	19	3
Size alternation (SA)		
Unspaced		
Lowercase	−25	−96
Mixed case	−42	−63
Spaced		
Lowercase	−20	−53
Mixed case	−24	−35
Case (C)		
Unspaced		
Consistent size	−36	−92
Alternating size	−53	−59
Spaced		
Consistent size	−23	−79
Alternating size	−27	−61
S × SA		
Lowercase	5	43
Mixed case	18	28
SA × C		
Unspaced	−17	33
Spaced	−4	18
S × C		
Consistent size	13	13
Alternating size	26	−2
S × SA × C	13	−15

Table 12
Analysis of Variance for Experiment 3

Subjects analysis			Items analysis		
Source	*df*	*F*	Source	*df*	*F*
Word–nonword (W)	1	78.29***	Between items		
W × *S* within-group error	31	(140,278.15)	W	1	1,476.32***
Case (C)	1	44.96***	*S* within-group error	478	(57,380.96)
C × *S* within-group error	31	(8,223.24)	Within items		
Size alternation (SA)	1	33.34***	C	1	117.75***
SA × *S* within-group error	31	(7,632.42)	W × C	1	11.43***
Spacing (S)	1	2.51	C × *S* within-group error	478	(25,804.95)
S × *S* within-group error	31	(2,455.79)	SA	1	142.86***
W × C	1	13.29**	W × SA	1	18.32***
W × C × *S* within-group error	31	(3,435.22)	SA × *S* within-group error	478	(15,613.30)
W × SA	1	11.06**	S	1	1.67
W × SA × *S* within-group error	31	(3,390.28)	W × S	1	1.99
W × S	1	3.06	S × *S* within-group error	478	(35,008.20)
W × S × *S* within-group error	31	(2,024.63)	C × SA	1	0.32
C × SA	1	0.82	W × C × SA	1	4.77*
C × SA × *S* within-group error	31	(2,401.83)	C × SA × *S* within-group error	478	(19,520.51)
C × S	1	1.78	C × S	1	1.60
C × S × *S* within-group error	31	(2,933.78)	W × C × S	1	0.27
SA × S	1	9.04**	C × S × *S* within-group error	478	(40,720.37)
SA × S × *S* within-group error	31	(1,953.62)	SA × S	1	8.23**
W × C × SA	1	2.80	W × SA × S	1	2.02
W × C × SA × *S* within-group error	31	(3,602.12)	SA × S × *S* within-group error	478	(13,293.86)
W × C × S	1	2.49	C × SA × S	1	0.10
W × C × S × *S* within-group error	31	(670.99)	W × C × SA × S	1	3.51
W × SA × S	1	3.17	C × SA × S × *S* within-group error	478	(11,728.50)
W × SA × S × *S* within-group error	31	(1,535.98)			
C × SA × S	1	0			
C × SA × S × *S* within-group error	31	(1,600.96)			
W × C × SA × S	1	1.24			
W × C × SA × S × *S* within-group error	31	(1,148.19)			

Note. Values enclosed in parentheses represent mean square errors. S = subjects.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

on alternating-size stimuli. A Newman–Keuls test showed that only the effect on consistent-size stimuli was significant.

The results of Experiment 3 replicated those of Experiment 2, suggesting that the findings of Experiment 2 are not confined to a particular set of stimuli or to the use of only certain case manipulations. The conditions equivalent to those used in Experiment 2 were those using consistent-size lowercase stimuli and alternating-size mixed-case stimuli, and the results from these conditions are reproduced in the bottom half of Table 6 for comparison. Alternating case and size together disrupted nonword naming more than word naming. For words and nonwords alike, spacing the letters slightly increased RTs to lowercase consistent-size stimuli, and it reduced RTs to mixed-case alternating-size stimuli. The case-mixing disruption effect on both words and nonwords was reduced by spacing.

The error data did not show a speed–accuracy trade-off (see Table 10) and so were not subjected to further analysis.

Tests of the masking and grouping hypotheses. An examination of the results in correspondence with the predictions in Table 9 shows the following. Consider first the predictions of the masking hypothesis. The results go against the prediction that there would be no case-mixing disruption effect for letters of the same size. It can be seen from Table 11 that there was a case-mixing effect with both consistent- and alternating-size stimuli. Prediction 1B suggests that size alternation should have disrupted performance independent of case. However, RTs to mixed-case, alternating-size stimuli (e.g., HeArInG) were greater than to lowercase, alternating-size stimuli (e.g., hearing; see Table 10), in opposition to the prediction. For words, the size-alternation effect was greater with mixed-case than with lowercase stimuli; for nonwords, the data went in the opposite direction (see Table 11). This suggests that the disruptive influences on nonword naming may not have been identical to those on word naming.

Prediction 1C was also not supported by the data. Spacing did not significantly reduce RTs to lowercase, alternating-size stimuli (e.g., hearing; see Table 11). The size-alternation effects were greater on nonwords than on words (prediction 1D), but except for words whose case was also alternated, RTs were not reduced by spacing (prediction 1E). Further, nonword naming was also disrupted more than word naming if case was alternated and size was constant. This last result supports the theory that word naming is less disrupted by any type of visual interference because of top-down lexical facilitation (Mayall & Humphreys, 1996). In summary, most of the evidence from Experiment 3 goes against the lateral-masking hypothesis.

Now we consider predictions from the letter-grouping hypothesis. There are different forms of this hypothesis, according to whether grouping is thought to be based on letter size, case, or a combination of size and case (see Table 9). If letter grouping is based on size alone, the predictions match those from the masking hypothesis (i.e., size should have a disruptive effect independent of case). These predictions have already been shown not to hold. If letter grouping is based solely on case, then case alternation should disrupt performance independent of size, and spacing should reduce the case-alternation effect (prediction 2B). This prediction was not supported by the results. We found that the processing of stimuli with consistent-size, mixed-case letters (e.g., HeArInG) was not as disrupted as the processing of stimuli with alternating-size, mixed-case letters (e.g., HeArInG; see Table 10). Also, for consistent-size, mixed-case stimuli, spacing did not reduce RTs.

In contrast to the other accounts, the data are consistent with the proposal that case-mixing disruption effects are caused by inappropriate grouping of letters of the same case and size. When letters alternated in both case and size (e.g., HeArInG), performance was disrupted over and above the effects of mixed case or size alone (mixed size, 25 ms; mixed case, 36 ms; mixed size and case, 78 ms, for unspaced words with consistent- and alternating-size letters in lowercase and mixed case), although this interaction reached statistical significance only over items: $F_1(1, 31) = 2.12$, $MSE = 742.14$; $F_2(1, 239) = 4.29$, $MSE = 5{,}977.48$. Also, the only evidence for positive effects of spacing on performance emerged in the condition when there were words with mixed case and mixed letter sizes (a benefit of 19 ms).[3]

However, it should also be noted that grouping based on both letter size and case may not have been the only factor involved. In particular, there was also some disruption when words were presented with letters of lowercase, mixed size (e.g., hearing) and mixed case, same size (e.g., HeArInG), compared with plain lowercase stimuli (e.g., hearing). We take up this point in the General Discussion.

Task order effects. An ANOVA across subjects, which included task order as a variable, was conducted on the *word* naming data to investigate whether naming nonwords before words influenced performance. This analysis again produced significant main effects of case, $F_1(1, 30) = 49.80$, $MSE = 1{,}561.61$, and size alternation, $F_1(1, 30) = 41.57$, $MSE = 1{,}162.08$, and a significant Spacing × Case interaction, $F_1(1, 30) = 6.31$, $MSE = 1{,}014.43$. The main effect of order did not quite reach significance, $F_1(1, 30) = 3.49$, $MSE = 42{,}657.24$, though when nonwords were named before words, RTs to words were slower (568 ms vs. 519 ms). The only interaction involving order that was close to significance was Letter Size Alternation × Order, $F_1(1, 30) = 4.01$, $MSE = 1{,}162.08$, with the effect of letter size alternation being greater when nonwords were named first (36 ms vs. 19 ms).

The effect of task order that approached significance on word naming could have been due to readers being more likely to name a word nonlexically if nonwords had been named previously (although see Lupker et al., 1997). The greater effect of letter-size alternation after nonwords had been read may again reflect nonlexical naming, as the identification of individual letters may have been more important in nonlexical naming (see Experiment 2). Identification of the smaller letters may have been made more difficult by inappropriate letter grouping.

An investigation of task order on nonword naming again found significant effects of case alternation, $F_1(1, 30) = 32.96$, $MSE = 10{,}244.49$, size alternation, $F_1(1, 30) = 25.97$, $MSE = 9{,}380.41$, and Spacing × Size Alternation, $F_1(1, 30) = 10.62$, $MSE = 1{,}934.56$. The effect of task order on nonword naming did not reach significance, $F_1(1, 30) = 1.64$, $MSE = 414{,}971.47$, although when words were named before nonwords, the nonwords were named 103 ms faster (785 ms vs. 888 ms). The only interaction with task order that reached significance was Spacing × Size × Order, $F_1(1, 30) = 4.74$, $MSE = 1{,}934.56$. When nonwords were named first, spacing the alternating-size letters reduced RTs, although this increased RTs when words were named before nonwords (−20 ms vs. 12 ms). RTs to consistent-size stimuli were increased by spacing whether nonwords or words were named first, although the increase was greater when nonwords were named first (40 ms vs. 24 ms).

General Discussion

The three experiments described here suggest that there is more than one disruptive influence on word processing that is intrinsic to the case-mixing disruption effect. These separate influences provide information as to the nature of the visual units that mediate word recognition.

Causes of the Case-Mixing Effect

Experiments 1 and 2 demonstrated that the effects of case mixing cannot be entirely due to loss of transletter features because performance with mixed-case stimuli was facilitated when spaces were introduced between the letters. Also, there was no disruptive effect of spacing the letters in lowercase words. Instead, Experiments 1 and 2 favored the hypothesis that the case-mixing disruption effect was caused either by lateral masking of the lowercase letters or by the inappropriate grouping of letters of the same case and size (see Table 1).

Experiment 3 separated out the influences of letter-size alternation and letter-case alternation, which are confounded by the standard case-mixing manipulation used in Experiments 1 and 2. This provided evidence against the importance of lateral masking. Alternating letter size alone did not disrupt performance to the same extent as alternating both letter size and case. Also, spacing did not facilitate the naming of lowercase, mixed-size stimuli. Further, alternating case alone had a disruptive effect similar to that for alternating size alone.

Experiment 3 did, however, generate evidence favoring a role for inappropriate letter grouping in producing case-

[3] Spacing also produced a reduction in RTs for lowercase nonwords with varied letter sizes, but in this condition the error rate increased with spacing.

mixing disruption effects. In particular, "standard" mixed-case stimuli disrupted naming over and above effects of using either (a) mixed-case letters that were the same size or (b) alternating-size, lowercase letters. Such an effect, when case and size differences are combined, suggest that the major disruption with standard mixed-case stimuli occurs because there is grouping between letters based on both of these properties. With standard mixed-case stimuli, grouping impairs performance because inappropriate visual units interfere with access to the lexicon. The facilitatory effect of spacing is unique to such mixed-case stimuli, and it occurs because spacing disrupts grouping between letter units of the same case and size. In Experiment 3, the positive effect of spacing on nonwords was not as great as that on words, although it was equivalent for words and nonwords in Experiment 2. Automatic letter grouping may be less likely in the longer nonwords used in Experiment 3.

In addition to inappropriate letter grouping, the involvement of a second factor in case mixing is indicated by the finding that performance is impaired both with (a) same-case, different-size strings, and (b) different-case, same-size strings, though for both stimulus types there was no effect of spacing. The only possible disruptive influence that would be produced by both types of stimulus is the loss of transletter features. This was rejected as a main cause of the case-mixing disruption effect in Experiment 1, as the theory predicted both a disruptive effect of spacing on lowercase stimuli and no effect of spacing on mixed-case stimuli. Nevertheless, even if it is not the main cause of case-mixing effects, it may still be a contributory factor. Indeed, it may be that in Experiments 1 and 2, a single space between the letters was not enough to disrupt transletter features. The residual case-mixing effect with spaced letters may be attributed to the disruption of transletter features.

One further possible contributory influence on the case-mixing disruption effect is the involvement of multiple orthographic codes. More orthographic letter codes need to be considered when stimuli are presented in mixed case (for both upper- and lowercase letters). However, this is not of direct relevance to the question of the visual units mediating word recognition, and Experiment 3 provided evidence against the number of letter codes having more than a small contributory influence. According to the letter-code hypothesis, case alternation should have a disruptive effect independent of letter size, and spacing should have no influence on the effect. These were not the results obtained.

Though our data are consistent with case-mixing disruption effects being mainly due to inappropriate letter grouping, it would be useful to have further, direct evidence of this. Such evidence could be provided in various ways. For example, consider a naming task with mixed-case stimuli in which the uppercase letters spell a word that differs in identity from the whole string (e.g., *BeAuTy*). If the letter-grouping theory is correct, we would expect this type of stimulus to be named more slowly than stimuli in which uppercase letters do not spell a word. If the letters *B*, *A*, and *T* are automatically grouped, then the lexical entry for *BAT* will be activated on presentation on this stimulus, thus, interfering with the correct naming response to the word *beauty*. This is particularly likely to occur if the embedded word is of higher frequency than the word spelled by the whole string. In a related study, Behrmann, Moscovitch, and Mozer (1991) showed that making a lexical decision about an underlined word embedded in another word increased RTs compared with naming a word embedded in a nonword (e.g., *farm* vs. *garm*), suggesting automatic processing of complete lowercase words. In a similar way, an effect of an uppercase embedded word on naming mixed-case stimuli would indicate the automatic grouping of the uppercase letters.

Visual Units That Mediate Word Recognition

The experiments described here provide evidence as to the visual units that mediate word recognition. First, our results suggest that reading uses visually based letter clusters of the same size and case. Inappropriate grouping between such clusters seems to be particularly disruptive when standard mixed-case stimuli are presented. Second, there is some indication that transletter features—features that are larger than single letters but smaller than whole words—are involved. In addition to these supraletter units, we would not wish to deny a role for single-letter information, which may be encoded in a relatively abstract form for access to the lexicon (e.g., Evett & Humphreys, 1981). The effects of case mixing we have observed could be operating on top of lexical-access processes based on abstract letter identities. The results favor a model of visual word processing in which lexical access is based on units coded at multiple levels: single letters, transletter features, and familiar letter groups (that are the same size and case), but not on units for whole words (Haber, Haber, & Furlin, 1983; Wheeler, 1970).

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