The Effects of Case Mixing on Word Recognition: Evidence from a PET Study

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Abstract

■ The early stages of visual word recognition were investigated by scanning participants using PET as they took part in implicit and explicit reading tasks with visually disrupted stimuli. CaSe MiXiNg has been shown in behavioral studies to increase reaction times (RTs) in naming and other word recognition tasks. In this study, we found that during both an implicit (feature detection) task and an explicit word-naming task, mixed-case words compared to same-case words produced increased activation in an area of the right parietal cortex previously associated with visual attention. No effect of case was found in this area for pseudowords or consonant strings. Further, lowering the contrast of the stimuli slowed RTs as much as case mixing, but did not lead to the same increase in right parietal activation. No significant effect of case mixing was observed in left-hemisphere language areas. The results suggest that reading mixed-case words requires increased attentional processing. However, later word recognition processes may be relatively unaffected by the disruption in presentation. ■

INTRODUCTION

In order to investigate the visual units that mediate word recognition, many behavioral studies have examined the effects of disrupting the visual form of words. In doing this, it is possible to change some potential visual units while leaving others intact. For instance, a common method of disrupting word form has been to use MiXeD cAsE stimuli (e.g., Mayall & Humphreys, 1996; Besner & McCann, 1987). Case mixing slows word-naming latencies. The cause of this effect is likely to be related to the visual units that normally mediate word recognition, which are altered by case mixing. For example, wholistic word shape will be disrupted by mixing the case of letters within words, as will "transletter features"—features larger than single letters but smaller than whole words (e.g., Mayall, Humphreys, & Olson, 1997; Mewhort & Johns, 1988). If wholistic word shape or transletter features are normally used in reading, changes to these features may force readers to rely more heavily than usual on letter-level analysis. This reliance on letter-level analysis could increase the attentional demands of word recognition as more smaller units would need to be processed, and there may be consequent increases in reaction times (RTs). In addition to wholistic word shape and transletter features, it is also possible that letter processing itself is disrupted by case mixing. For example, lowercase letters within words may be masked by their larger uppercase neighbors. Overcoming this masking may again increase demands on attentional processes, and slow RTs. In the present study, we use functional neuroimaging to investigate the case-mixing effect, to assess whether case mixing is associated with increased activation in selective parts of the reading system. In particular, we investigated whether case mixing leads to increased activation in cortical areas associated with linguistic processing, or whether its effects are more pronounced on cortical areas associated with visual processing or attention. We also assessed performance in an implicit as well as an explicit reading task (detecting a gap in a letter within a letter string and naming the strings, respectively), to test the degree to which activation in brain areas is modulated automatically by case mixing. We discuss first studies that have used imaging to measure brain sites associated with different stages in reading, before discussing evidence for automatic processing in implicit reading tasks.

Stages of Word Recognition and Naming

Models of word recognition derived from cognitive and cognitive neuropsychological studies assume that recognition is contingent on a number of processing stages. The first stage involves visual analysis of a word, leading to the activation of orthographic (spelling) representa-

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tions of known words, sometimes referred to as the ''visual input lexicon'' or ''visual word-form system'' (e.g., see Shallice & McCarthy, 1985; Morton & Patterson, 1980). Access to orthographic representations is followed by access to semantic and phonological associations. To account for correct naming of nonwords though, phonological retrieval must also operate at a sublexical level to allow constituent letters or letter groups to be converted into sounds (cf. Plaut, McClelland, Seidenberg, & Patterson, 1996; Coltheart, Curtis, Atkins, & Haller, 1993).

Functional neuroimaging has revealed that different parts of the neural network mediating word recognition can be associated with some of the different cognitive stages in word-processing models. The full neural network associated with reading single words silently or aloud includes a number of distinct regions in the left hemisphere (see Moore & Price, 1999; Price et al., 1994; Price, Moore, & Frackowiak, 1996; Price, Wise, & Frackowiak, 1996; Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995). These include both frontal areas (in the posterior inferior frontal gyrus and frontal operculum) and temporal areas (in the posterior inferior, middle and superior temporal gyri, and temporo-parietal cortices). In addition, areas involved in motor control (precentral cortices, cerebellum and supplementary motor cortex) are activated even when subjects are reading silently, and areas involved in auditory processing (bilateral auditory cortices) are activated when subjects are reading aloud because they hear the sound of their spoken response (Price, Moore, et al., 1996, Price, Wise, Warburton, et al., 1996). Finally, extrastriate visual areas (fusiform and lingual gyri) can be activated during reading (particularly reading aloud). Although this area has previously been associated with the visual word-form area (Petersen, Fox, Snyder, & Raichle, 1990), it has also been suggested that increased extrastriate activity during reading reflects enhanced attention to the visual structure of the word (Mechelli, Humphreys, Mayall, Olson, & Price, 2000; Moore & Price, 1999; Price, Moore, & Friston, 1997). Only the latter proposal accounts for why the same areas are equally responsive to reading and picture naming (Moore & Price, 1999; Bookheimer et al., 1995).

Differentiating the role of the different reading areas has not been straightforward. For instance, while it was initially expected that words would activate semantic regions more strongly than pseudowords (Herbster, Mintun, Nebes, & Becker, 1997; Rumsey et al., 1997; Price, Wise, & Frackowiak, 1996; Petersen et al., 1990), this has not always been the case, possibly because during pseudoword reading subjects implicitly search for the (missing) meaning (see Price, Wise, & Frackowiak, 1996). Nevertheless, the role of the different reading areas has been revealed by, for instance, asking subjects to focus on the relative meaning or phonology associated with words (Price, Moore, Humphreys, & Wise, 1997; Pugh et al., 1996) or comparing reading with picture naming (Moore & Price, 1999; Price & Friston, 1997a; Bookheimer et al., 1995). On the basis of these studies, the following hypotheses have been proposed (Price, 1998, 2000). First, phonological retrieval irrespective of stimulus (words, pictures, letters, colors) activates the left lateral posterior inferior temporal cortex and the left frontal operculum. Second, the dorsal surface of the superior temporal gyrus and the neighboring left anterior temporo-parietal cortex are involved in assembling phonology. This has been proposed because these areas are activated by reading words (particularly pseudowords), but they are not involved in picture naming (see Moore & Price, 1999; Bookheimer et al., 1995). Other regions of the left posterior temporal cortex (the medial and anterior inferior temporal cortex, posterior middle temporal, and posterior temporo-parietal junction) have been associated with semantic processing because these areas are more active for semantic relative to perceptual tasks (Ricci et al., 1999; Mummery, Patterson, Hodges, & Price, 1998; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996; Démonet et al., 1992; Démonet, Price, Wise, & Frackowiak, 1994). Finally, when words make up sentences, activation increases in the inferior frontal and anterior temporal regions (Dapretto & Bookheimer, 1999; Bottini et al., 1994). These areas appear to play an important role in either semantic or syntactic processing.

If case mixing increases the visual, semantic, or phonological processing carried out on words, then we might expect additional activation in the brain areas associated with each process when words appear in mixed case. However, as we have noted, case mixing may also lead to the stronger involvement of visual attention in reading. If this is the case, at least two outcomes seem possible. One is that extra areas involved in visual attentional control and selection are recruited when mixed-case words are read. In a meta-analysis of imaging studies on visual attention control and scanning, Corbetta and Shulman (1998) reported frequent increases in the intraparietal and postcentral sulci, particularly in the right hemisphere, when the demands of visual attention increase. These same areas are activated both when saccadic eye movements are made and when there are covert shifts in visual attention (though additional areas are recruited when eye movements take place). Furthermore, when attention to words is maximized by reducing the stimulus duration, activation in right parietal and frontal regions increases (Price & Friston, 1997b). The processing of written stimuli presented in mixed case is likely to increase attentional requirements and it may produce more serial processing of letters, either due to an increase in lateral masking or due to a reliance on letter-level processing caused by the disruption of larger visual units. If this is the case, we might expect to see an increase in activation in right parietal areas associated with mixed-case presentation due to either an increase in covert shifts of attention or eye movements.

A somewhat different possibility, however, comes from imaging studies that have examined selective attention to stimulus dimensions in search. Here it has been found that attention increases activation at neural sites linked to the processing of the specific dimensions (e.g., Corbetta, Shulman, Miezin, & Petersen, 1995). Increased attentional demands during reading also leads to increased activation of brain areas associated with processing the visual features of words. For example, in a previous study of the current data, we have demonstrated (Mechelli et al., 2000) that when the visual contrast of words is lowered (by presenting light-grey rather than white words on a mid-grey background), activation increases in the medial lingual gyrus associated with local feature processing by Fink et al. (1997). Conversely, lowering visual contrast decreases activation in the posterior fusiform gyri associated with global feature processing by Fink et al. This is consistent with reductions in visual contrast leading to increased attention to local visual features. Case mixing may elicit similar effects. To examine this, contrast reduction in addition to case mixing was included as a variable in this study. This also allowed us to test whether any effects of mixed-case presentation were due simply to an increase in the demands on visual processing. In a pilot study, a level of contrast reduction was derived, which increased naming latencies to six-letter words to an equivalent extent as case mixing. This was done by using a psychophysical step function and alternating blocks of mixed-case and low-contrast words. If case-mixing effects are due to increased demands on visual processing, then equivalent effects should be found for case mixing and contrast reduction.

Automatic Processing of Words

Several behavioral studies have suggested that we can access the meanings and phonological representations of words that appear in our field of vision even when this is unnecessary for the task being conducted (e.g., Coltheart, Patterson, & Leahy, 1994; Van Orden, Johnston, & Hale, 1988; Stroop, 1935). In a previous PET study of implicit reading, Price, Wise, & Frackowiak (1996) found that most of the cortical areas associated with explicit reading (see above) were activated by the presence of words (relative to consonants or false fonts) when subjects were engaged in an irrelevant perceptual task, which was held constant irrespective of the stimulus. This suggests that words did access stored knowledge, even though it was unnecessary for the task. Here we assessed whether effects of case mixing modulated processing in similar ways in implicit and explicit reading tasks. Similar effects across the tasks would suggest that case-mixing effects modulate automated reading processes.

Figure 1. Example of stimulus used in the gap detection task.

The Experiments

Experiment 1 here examines the effects of case mixing on an implicit reading task. We ask whether case mixing modulates automatic word processing, and whether any specific effects of case mixing are linked to changes in brain regions associated with linguistic or visual attentional processing.

In previous studies of implicit reading, participants have been required to detect the presence of ascending letters in lowercase strings (Brunswick, McCrory, Price, Frith, & Frith, 1999; Buechel, Price, & Friston, 1998; Price, Wise, & Frackowiak, 1996). Clearly, it was not possible to use this task here as half of the letters presented were in uppercase and, therefore, did not have ascenders equivalent to those of lowercase letters. Thus, an extra feature (a gap) was introduced into half of the stimuli, and participants were asked to detect this gap. The stimuli were words, pseudowords, and unpronounceable consonant strings, which, on any trial, could have a gap in one of the letters (see Figure 1). Hence, access to any stored knowledge from words was irrelevant to the task. We also included a third variable—luminance contrast which was either high or low. This allowed us to establish whether the effect of case mixing corresponded to the effect of reduced contrast.

In Experiment 2, we examined the brain areas activated in the explicit reading of same and mixed-case words. Participants named words rather than making gap detection judgements to them. Here we assessed whether language areas in the left hemisphere were activated by mixed- relative to same-case words if the naming task was explicit rather than implicit. Since the major effects of case mixing in Experiment 1 were confined to words, we only examined effects with words in Experiment 2. There were two additional variables: word length (3, 6, or 9 letters) and luminance contrast (as in Experiment 1).

RESULTS

Behavioral Measures During Experiment 1

Mean RTs and percentage errors for the gap detection task in Experiment 1 can be seen in Table 1. An analysis of variance on RTs indicated that there was a significant effect of contrast reduction [$F(1,5) = 13.59$, $p < .05$] and the effect of case mixing was close to significance [$F(1,5) = 5.47$, $p = .07$]. There was no effect of stimulus type [$F(2,10) = 0.18$, $p = .84$]. An analysis of variance on the error data again produced a significant effect of contrast reduction [$F(1,5) = 15.00$, $p < .05$] and the main effect of case mixing was again close to significance [$F(1,5) = 5.99$, $p = .06$]. There was also a significant interaction of Case Mixing × Stimulus Type [$F(2,10) = 4.82$, $p < .05$]. A Newman–Keuls test indicated that that there was a significant effect of case mixing on words ($p < .01$) and pseudowords ($p < .05$), but no effect on consonant strings. In a larger-scale behavioral study, we have found significant effects of both contrast reduction (high faster than low) and case mixing (same-case faster than mixed-case) on RTs. Too little data were collected here to provide a strong test of the effects on overt behavior, but we note that the effects of contrast reduction were at least as strong as those of case mixing.

Neural Activations

All results presented were significant at the $p < .05$ corrected for multiple comparisons level unless otherwise stated. MNI coordinates refer to the location of maximal activation.

The Effect of Mixed–Same Case

The conjunction of mixed–same-case words in Experiments 1 and 2 revealed a large area of activation in the right superior parietal lobe (peak: $x = +48$, $y = -42$, $z = +56$; $Z = 4.7$, p[corrected] = .025), which extended into the right premotor cortex ($x = +54$, $y = -6$, $z = +28$; $Z = 4.3$, p[corrected] = .143) (see Figure 2). The size of the effect was equivalent in Experiment 1 ($Z = 3.7$) and Experiment 2 ($Z = 3.4$); over experiments, for low contrast ($Z = 3.8$) and high contrast ($Z = 3.9$); and within Experiment 2 for three-letter words ($Z = 2.7$), six-letter words ($Z = 3.2$), and nine-letter words ($Z = 2.4$). Indeed, there were no significant interactions between case and contrast (in either experiment) or case and word length (Experiment 2) even when the threshold was lowered to $p < .05$ uncorrected for multiple comparisons ($Z = 1.64$).

However, activation in this right parietal area did not reach significance when the mixed-case minus same-case conjunction included pseudowords and consonants. This was explained by a highly significant interaction between case (mixed–same) and word type (words relative to pseudowords and consonants) in Experiment 1 (peak: $x = +40$, $y = -46$, $z = +56$; $Z = 4.7$, p[corrected] = .025). As can be seen in Figure 2, the interaction arose because right parietal activation was least in the presence of same-case words ($Z = 3.2$ for pseudowords minus words in same case; $Z = 2.9$ for consonants minus words in same case).

There were no other significant effects of case (including same relative to mixed) for either Experiment 1 or Experiment 2. The results therefore indicated that left-hemisphere linguistic areas were not affected by case. However, it is possible that small effects in linguistic areas were not detected because of the strict threshold applied. To qualify an absence of activation, we therefore lowered the statistical threshold to $p < .001$ uncorrected and looked for effects of case in left-hemisphere language areas. In addition, to demonstrate the relative sensitivity of our design, we report the effects of word length, contrast, and implicit reading (words and pseudowords relative to consonants).

Less Significant Effects of Case in Left-Hemisphere Language Areas

At an uncorrected significance threshold ($p < .001$), two effects of mixed relative to same case were observed in the left hemisphere. Neither was significant for all word lengths. One was in the left superior temporal sulcus (peak: $x = -50$, $y = -12$, $z = 0$), where the greatest activity was apparent for nine-letter words in mixed case ($Z = 3.3$ for nine-letter words in mixed relative to same case). The other was in the left premotor area (peak: $x = -58$, $y = -14$, $z = 40$), where activity was least for three-

Table 1. Mean RTs, Standard Deviations, and Percentage Errors in Gap Detection Task (msec)

		Word			*Pseudoword*			*Consonant String*		
Case	*Contrast*	*RT*	*SD*	*Error*	*RT*	*SD*	*Error*	*RT*	*SD*	*Error*
Same	High	460	33	2	482	72	2.2	474	43	3.6
	Low	501	64	2.2	517	51	3.7	502	52	5.2
Mixed	High	494	58	3.7	486	62	3.7	496	61	2.7
	Low	519	46	5.6	513	43	5.2	519	44	5.6

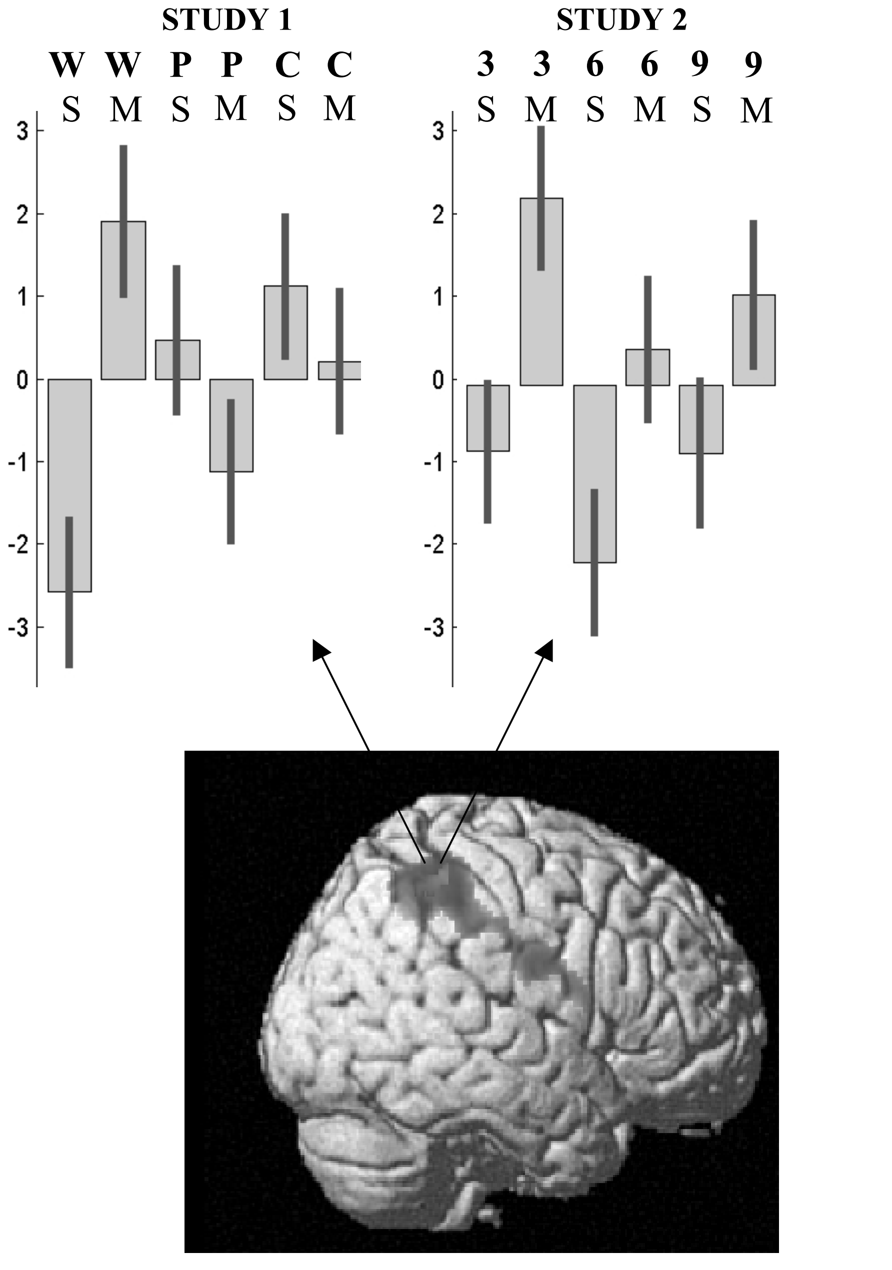

Figure 2. Region of right parietal cortex where rCBF increased for mixed-case words compared to same-case words across Experiments 1 and 2.

and six-letter words in same case ($Z = 3.6$ for three- and six-letter words in mixed relative to same case). The left superior temporal area is typically associated with speech perception (Binder et al., 2000), but has also been associated with making phonological decisions on words and pictures (Moore, unpublished Ph.D. thesis). It is therefore possible that phonological processing of nine-letter words in mixed case is enhanced. Similarly, the left premotor area is involved in articulation. Least activity for three- and six-letter words in same case suggests that nine-letter words and shorter words in mixed case increase the demands on articulation.

At the uncorrected significance threshold ($p < .001$), there were also some potentially interesting effects for same relative to mixed case. For all conditions (including pseudowords and consonant strings), there was more activation for same case in the left middle temporal cortex (peak: $x = -54$, $y = -38$, $z = -14$; $Z = 4.2$). For three- and six-letter words in Experiment 2 (but not for six-letter words in Experiment 1 or nine-letter words in Experiment 2), activation for same case was above all other areas in a region associated with semantic processing (peak: $x = -54$, $y = 6$, $z = -22$; $Z = 3.7$). Finally, for three-letter words (Experiment 2 only), there was more activation in the left anterior temporo-parietal cortex (peak: $x = -64$, $y = -36$, $z = 18$; $Z = 4.4$). Interestingly, a nearby region ($x = -64$, $y = -28$, $z = 24$) was significantly more active for pseudowords relative to words ($Z = 4.5$; $p < .05$ corrected) in Experiment 1.

Although the effects of case at an uncorrected level are potentially interesting, they were not qualified by significant interactions. Therefore, replication is required before strong interpretations can be made. Our point is that we see effects of case in the right parietal cortex that are highly significant and word-specific, whereas effects in left hemisphere areas are small and specific to word length.

Other Significant Effects

In Experiment 1, there was a strong effect of high relative to low contrast in the right posterior fusiform ($x = +36, y = -82, z = -8; Z = 4.7; p < .01$). The same area was observed for high relative to low contrast in Experiment 2 (peak: $x = +38, y = -92, z = -8; Z = 4.5$, $p < .05$ corrected for conjunction across experiments). There were no significant effects of low contrast across experiments and even when the threshold was reduced to $p < .05$ uncorrected, there was no effect of low contrast in the right parietal area associated with mixed relative to same case.

In Experiment 2, there were strong effects of word length. These were seen in medial and left posterior fusiform and right anterior fusiform (peaks: $x = +8, y = -84, z = -2; Z = 6.7; x = -12, y = -92, z = -2; Z = 6.4$; $x = +24$, $y = -58$, $z = -10$; $Z = 5.0$, $p < .01$ corrected).

Finally, in Experiment 1, words and pseudowords relative to consonants elicited activation in several language areas including Wernicke's area ($x = -66$, $y = -32$, $z = 2$; $Z = 3.7$), left inferior temporal areas ($x = -44, y = -22, z = -22; Z = 4.2; x = -54, y = -4$, $z = -16; Z = 3.5$), bilateral motor cortex ($x = -54, y = +2, z = +44; Z = 3.9; x = +62, y = -20, z = 42; Z = 3.9$) and the left thalamus ($x = -16, y = -2, z = 16; Z = 4.4$).

Summary of Results

There were highly significant effects of mixed-case relative to same-case words in the right superior parietal cortex irrespective of task, word length, and contrast. There were also highly significant effects of contrast and word length in areas of the visual cortex. In contrast, effects of case in linguistic areas were small and word length-specific.

DISCUSSION

The major finding of these studies is that there was increased activation in areas in the right parietal lobe previously associated with the recruitment of visual attention (Corbetta & Shulman, 1998), when words occurred in mixed relative to same case. The effect was not apparent for pseudowords or consonant strings, and the same effect was not found for contrast reduction (though contrast reduction generated an equivalent effect on behavior).

In behavioral studies of overt word processing, it is well established that case mixing slows reading. Our PET data are consistent with this, with there being increased activation for mixed-case over same-case words even in an implicit reading task (gap detection). Interestingly, these increases were greater for words than for pseudowords and nonwords in the gap detection task. This suggests that, even though the task in Experiment 1 did not require access to word representations, this still took place, indexed by the selective changes in neural activation. We note that these activation changes were apparent even though the behavioral data from the study failed to demonstrate differences between different types of letter string on RT performance in the gap detection task (although the increase in errors was greater for mixed-case words than for mixed-case pseudowords or consonant strings).

The primary activation change linked to case mixing was in an area of the right parietal lobe, with the peak of activation at (48, −42, 56). Previous neurological studies and neuroimaging work link this area of the right parietal lobe with changes in visual attention. For instance, Corbetta and Shulman (1998) found activation in the right intraparietal and postcentral sulci when participants were required to shift attention to peripheral areas of their visual field. Similarly, damage to right parietal areas is classically associated with disorders of visual attention, such as unilateral neglect (Heilman & Valenstein, 1993). The same area with a peak of activation at (40, −50, 56) has been found to be activated in a task requiring decisions as to whether lines were bisected centrally, relative to a control condition requiring decisions as to whether the line was bisected at all (Fink et al., 2000). Poor performance in this type of line bisection task is classically associated with visual neglect, a disorder linked to impaired visual attention (Heilman & Valenstein, 1993). A similar area with a peak of activation at (31, −47, 54) was also found to be activated in a visual conjunction search task (Corbetta et al., 1995). Search for a conjunction (e.g., an item of both a particular color and a particular speed of movement) is usually thought to require increased attentional processing compared to a single-feature search task due to the need to adopt a serial search strategy.

Our finding that activation in this right parietal area is increased when words are presented in mixed case suggests that there may be an increased attentional demand when mixed-case words are processed. Consistent with this, word naming in a patient with right parietal damage has been shown to be severely disrupted by case mixing (Hall, Humphreys, & Cooper, 2001). Interestingly, our study suggests that any increase in attentional demands is not associated with mixing case per se, as, in the feature detection task of Experiment 1, the effect was far greater with words than with the other stimuli. We conclude that words in standard case may be read with relatively little attentional involvement. However, when in mixed-case format, attentional processes may be recruited to help overcome the disruptive effect of the unusual letter formats. With nonwords and pseudowords, attentional processes may be called on with both same- and mixed-case formats, so there is little extra increase in attentional regions for mixed-case relative to same-case strings. With nonwords and pseudowords, attention may be recruited for the gap detection task—either to enhance parallel encoding of the features present, or to generate serial, letter-based processing. With words in their usual (same case) format this may not be necessary, hence, the reduced activation in the right parietal area for same-case words relative to pseudowords and consonants (see Figure 2 and the Results section for more details). For example, top-down feedback from lexical representations may enhance feature processing, enabling the target gap to be detected. This is consistent with interactive models of word recognition (e.g., McClelland & Rumelhart, 1981). Any increase in attentional processing is unlikely to be due to increased attention to the gaps in Experiment 1, since the same effect of case mixing was found in the overt naming task of Experiment 2.

Despite the strong effect of case mixing in the right parietal cortex, effects in the left-hemisphere language areas (i.e., in the left temporal, frontal, or even extrastriate cortices) were small. The imaging data are therefore consistent with the idea that case mixing mainly affects early stages of word recognition, and that increased processing at these early stages may allow normal processing in the later lexical stages involved specifically with language processing.

Despite the strong effects of case mixing that we observed, there was no effect of contrast reduction in the right parietal cortex, even though processing reduced-contrast words was as difficult as processing mixed-case words (see Table 1). Indeed, contrast reduction has previously been shown to affect occipital areas associated with early visual processing (Mechelli et al., 2000). Therefore, the effect of case mixing is not simply due to an increase in early visual processing. Taken together with previous associations of the right parietal cortex and visual attention, the increase in processing in this area may be best interpreted as an increase in attentional processing.

An obvious question of interest is why case mixing may increase demands on attentional processes. There are several possibilities. Firstly, in normal word recognition, visual units of different sizes may be processed in parallel, for example, letters, transletter features, and wholistic word shape. Evidence in the behavioral literature suggests that wholistic word shape may not play an important role in word recognition (Mayall et al., 1997; Paap, Newsome, & Noel, 1984), however, there is evidence for the use of transletter features (Hall et al., 2001; Humphreys & Mayall, in press; Dickerson, 1999; Mayall et al., 1997; Whiteley & Walker, 1994). These features are larger than single letters, hence they will be disrupted by case mixing. This may, in turn, lead to a greater reliance on letter-level analysis. Letter-level analysis is likely to involve processing of a larger number of visual units compared to reading based on transletter units. Attention may be recruited to enable more visual units to be processed in parallel.

Alternatively, presenting words in mixed case may also induce serial processing of letters. Consistent with this, a behavioral study has shown case-mixing effects to increase with word length (Mayall, Olson, & Humphreys, in preparation). A serial processing strategy would again increase attentional involvement in performance and also possibly the involvement of eye movements. Previous work has shown that the brain regions mediating covert shifts of attention and eye movements are very similar (Corbetta & Shulman, 1998). We note, however, that there was no increase in activation in the cerebellum or the frontal eye fields here, which have previously been found when eye movements are made.

A further possible cause of the case-mixing effect is the lateral masking of lowercase letters by their larger uppercase neighbors. Attention may be recruited to overcome masking effects. Against this, though, we found only minimal changes in activation for pseudowords and consonant strings in Experiment 1. Masking should reduce the discriminability of the gap in these strings as well as in words, leading to increased activation when these strings appeared in mixed case. We did not find this. There is also little behavioral data favoring a masking account of case-mixing effects (see Mayall et al., 1997). Rather, the data suggest that case mixing was associated with a change in attentional processing for words only. Words presented in same-case format may normally be processed with minimal attentional involvement. With mixed-case words, and pseudowords and nonwords, an increase in attention may be required.

In conclusion, the major effect of disrupting the visual form of words by mixed-case presentation was to increase activation in neural areas associated with attentional processing. Attention may be recruited in parallel across stimuli to facilitate feature processing, or it may modulate the serial processing of letters. When presented with letters in the same case, though, words may be read implicitly, with relatively little attentional involvement. Once attentional processes have been differentially activated by mixed-case words, later (linguistic) stages of word recognition may be relatively unaffected by case.

METHODS

Participants

Twelve healthy males with normal or corrected-to-normal vision participated in this study. All were right-handed, had English as their first language, had no history of reading difficulties, were fully informed of the procedure, and signed written consent forms before testing began.

Design

The study comprised two distinct experiments. Each had 6 participants and 3 factorially manipulated variables. The variable of interest in both experiments was letter case (either SAME or MiXeD) and this was always manipulated with luminance contrast (either high or low). The third variable was stimulus type, which varied across experiments. In Experiment 1, the stimuli were six-letter words, six-letter pseudowords, or six-letter consonant strings. There were 180 of each. Words had a frequency of between 50 and 246 occurrences per million (Kucera & Francis, 1967). Pseudowords were created by changing the order of letters in words so that they no longer spelled a real word, but were still pronounceable, and consonant strings were created by replacing the vowels in pseudowords with other consonants. In Experiment 2, the stimuli were three-letter words, six-letter words, and nine-letter words. Again, there were 180 of each. Word frequency was between 1 and 18 occurrences per million (Kucera & Francis, 1967) for each word length.

Overall, there were 12 (blocked) conditions per experiment with no replications within subject. Therefore, condition order and stimulus type was controlled across subjects. Each set of 180 words/letter strings (see above) was divided into 4 sets of 45, matched for word frequency. Within subject, one set was presented in SAME case/high contrast, one as SAME case/low contrast, one as MiXeD case/high contrast and one as MiXeD case/low contrast. Across subjects, case and contrast were rotated over set.

Within blocks of same-case stimuli, case was alternated every trial (i.e., half the stimuli were presented in lowercase and half in uppercase). Uppercase letters were 11 mm tall and lowercase letters 8 mm, both having a width of approximately 4 mm. The viewing distance was 40–60 cm. Each stimulus was presented for 1000 msec at a rate of 1 per 1.5 sec (500 msec ISI). The total stimulus presentation time was therefore 67.5 sec (45×1.5 sec).

Task

Task was held constant within but not between experiments. In Experiment 1, an explicit reading task was not possible because consonant strings are not pronounceable. We therefore adopted a "feature detection" task where reading responses to words and pseudowords occur implicitly (i.e., without instructions to read) (see Price, Wise, & Frackowiak, 1996 and the Results section). The feature used in Experiment 1 was a small "gap" introduced into one of the letters in half of each type of stimuli (see Figure 1). The task was to press a key if there was a gap present in the stimulus but no response was required when there was no gap present. In Experiment 2, all stimuli were words and the subjects were instructed to articulate the corresponding phonology without generating any sound. This approach is referred to as "mouthing" and is used here, and in several previous experiments, because it forces the subject to read the words, enables the investigator to check responses by lip reading from a video monitor, and does not result in extensive bilateral activation of auditory cortex due to processing generated sounds (see Price, Moore, et al., 1996).

Data Acquisition

Twelve PET scans (one per condition) were acquired for each participant using a Siemans/CPS Ecat HR+(962) head scanner with a field of view of 15.5 cm. Subjects received a total of 350 MBq of $H_2{}^{15}O$ infused over 20 sec through a forearm cannula. Each scan lasted 90 sec followed by an 8-min interscan interval. Stimulus presentation started 10 sec prior to scanning and continued through the 45-sec critical uptake window. Images were reconstructed into 63 planes using a 0.5 Hanning filter, resulting in a nominal in-plane resolution of 6.4 mm.

Data Analysis

The data were analyzed with Statistical Parametric Mapping (SPM99; Wellcome Department of Cognitive Neurology, London, UK) implemented in Matlab (Mathworks, Sherbon, MA, USA). Prior to statistical analysis, the images for each participant were realigned using the first for reference, in order to correct for any head movements between scans. Realigned scans were spatially normalized then smoothed (16 mm kernal) to account for variations in gyral anatomy and individual variability in functional neuroanatomy and to improve the signal-to-noise ratio (Friston et al., 1995).

Data from both experiments were analyzed in a single design matrix specifying two groups (one per experiment) and 12 conditions per subject. Contrasts were balanced within experiment as follows:

Experiment 1:

1. Main effect of case (mixed–same and same–mixed)
2. The interactions between (a) case and stimulus type and (b) case and contrast
3. Simple main effects pertaining to significant interactions

Experiment 2:

1. Main effect of case (mixed–same and same–mixed)
2. The interactions between (a) case and word length and (b) case and contrast
3. Simple main effects pertaining to significant interactions

We then computed conjunctions of the effects of case over experiments. This allowed us to identify effects that are common to both experiments (as opposed to summed over experiments).

In addition, we looked at the main effect of contrast (Experiments 1 and 2); reading (Experiment 1) and word length (Experiment 2). Although these effects, summed over letter case, are not directly related to the aims of this article, they are included for completeness and for comparison with the effect of case.

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