# Pure alexia, letter-by-letter reading and word length effects are not synonymous: Evidence from visual distortion-induced length effects on normal word reading.

BAKER, S. S.[1], CAINE, D.[1], LACEY, E. H.[2], ESHAN, S.[1], JEFFERIES, E.[1] and LAMBON RALPH, M.A.[1]

[1]Neuroscience and Aphasia Research Unit, University of Manchester, UK.

[2]Interdisciplinary Program in Neuroscience, Georgetown University, Washington, DC

Correspondence about this article:

Dr. Diana Caine,

Neuroscience and Aphasia Research Unit (NARU)

School of Psychological Sciences (Zochonis Building)

University of Manchester

Oxford Road,

Manchester, M13 9PL.

Phone: +44 (0)161 276 0446

Fax: +44 (0)161 275 2873

Running head: Re-thinking the word-length effect of pure alexia

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**Abstract**

Pure alexia is an acquired reading disorder in which premorbidly literate adults lose the ability to read even single words efficiently and is classically characterised by pathologically high word length effects on reading times. Two classes of theory exist to explain the word-length effect and associated deficits in the disorder: one proposes damage to a brain region specific to word reading, whilst the other suggests that the problem is the result of a generalised visual impairment. The latter theory predicts that visually distorting words will induce a word-length effect in normal readers. We tested this prediction in two experiments that explored the effects of word shape (alternating letter size) or letter identity distortions (low pass spatial frequency filtering). Each of these two very different types of distortion induced length effects in normal readers as well as visually-related reading errors (another feature of pure alexia). These demonstrations add to existing evidence in the literature that (a) a wide variety of visual distortions induce length effects in normal reading and (b) that a number of disparate neurological conditions/lesion locations lead to length effects in abnormal reading. Taken together these results indicate that word-length is not a pathognomonic symptom of pure alexia but rather the emergent effect of a number of different kinds of deficit of which degraded visual input is one.

**Introduction**

Pure alexia (letter-by-letter reading; LBL) is an acquired reading disorder in which previously literate adults lose the ability to read even single words normally, while writing, spelling and other cognitive abilities appear to remain unaffected (Patterson & Kay, 1982). The feature currently considered to be diagnostic of the disorder is increasing latency with word length: the time taken to identify a word is linearly proportional to the number of its constituent letters (Price & Humphreys, 1992; Shallice & Saffran, 1986). The extent of the impairment can vary widely from patients who show a word-length effect of only 97 milliseconds per additional letter (Behrmann *et al.*, 1998a) to more severe cases with a word-length effect as great as 9.6 seconds per additional letter (Lambon Ralph *et al.*, 2004).

Word length effects are generally considered to be a pathognomonic symptom of pure alexia. There are already some indications, however, that this may not be the case. A number of distinct patient groups show length effects when their reading times are measured. This includes classical patients with pure alexia after occipitotemporal lesions but also patients with lesions restricted to primary visual cortex (hemianopic alexics: (Leff *et al.*, 2001), patients with parietal lesions ((Warrington & Shallice, 1979), as well as patients with semantic dementia (whose progressive atrophy is centred upon the anterolateral temporal lobes: {Cumming, 2006}. Because investigation of so-called letter-by-letter reading has focussed on patients selected for study on the basis of a length effect, it is possible that amongst reported cases a variety of patient types are represented, with different underlying causes for the length effect. This has obvious consequences for theories of LBL and pure alexia.

One theory of LBL reading in pure alexia has argued that it results from damage to neural mechanisms located in the left occipital-temporal region (Binder & Mohr, 1992; Damasio &

Damasio, 1983), that are uniquely tuned for word recognition. On this account, the deficit is regarded as a specific impairment of reading (Hanley & Kay, 1996; Saffran & Coslett, 1998; Warrington & Shallice, 1980). Functional MRI studies in normal readers have indeed localised a cortical region in the left posterior fusiform gyrus, the so-called 'Visual Word Form Area' (VWFA), that shows greater activation when subjects read words compared to pronounceable nonwords (Cohen et al., 2000; Cohen et al., 2002). It has also been shown that this area is involved in the majority of LBL readers (Cohen et al., 2003; Henry et al., 2005).

An alternative approach is that LBL reading results from a general visual problem, to which reading may be more susceptible than other visual processing tasks, but the impact of which is not exclusive to reading (Behrmann *et al.*, 1998b; Farah, 1991). It has been shown, for example, that the so-called VWFA is activated not only by words but also during other visual tasks including the naming of colours and of objects, and by non-visual tasks as well (Price & Devlin, 2003). According to this alternative view, LBL reading is regarded as an emergent effect of a more general, if subtle, visual disturbance.

From a theoretical perspective, the 'visual deficit' account is consistent with the primary systems hypothesis (Plaut *et al.*, 1996). This holds that acquired disorders of reading do not occur in isolation but derive instead from damage to one of the three principal, and ontogenetically prior, components of language (orthography, phonology, semantics) or from damaged input to them (Lambon Ralph & Patterson, 2005). Here, LBL reading in pure alexia is attributable to a deficit in the processing of orthography resulting from damage to the visual system. A prediction that follows from this is that patients with pure alexia will also show other deficits in visual processing, if tested appropriately. When carefully investigated, these patients are in fact poor at a number of non-reading visual tasks including object matching (Farah &

Wallace, 1991), object discrimination (Sekuler & Behrmann, 1996) and object naming (Behrmann et al., 1998a; Friedman & Alexander, 1984). These results are consistent with the findings from computational models of visual word recognition; when the visual input to these models is impaired, the slowed build up of activation demonstrates an emergent length effect (longer words take a longer time to reach threshold and/or require a greater number of re-fixations (Behrmann et al., 1998b; Lambon Ralph et al., 2004).

A second prediction is that if the patients' deficit reflects a degraded incoming visual signal, then it ought to be possible to provoke a word-length effect in normal readers if they are exposed to visually degraded stimuli. Normal readers are thought to process the letters of words simultaneously and have been found to show either no (Weekes, 1997), or only a small length effect in word reading, which requires a large number of participants/items to reach statistical significance (Balota *et al.*, 2004; Richardson, 1976). A number of studies have shown that visual distortions can produce a word-length effect in normal readers comparable to those of pure alexics. These include the presentation of words in peripheral vision (Legge *et al.*, 2001) and masking by a random line pattern (Farah and Wallace, (1991). In an elegant recent report, Fiset et al. (2006) utilised reduced contrast and spatial frequency filtering to induce LBL reading in a group of normal participants. Indeed, using this method, Fiset et al. were able to simulate reading data from the more severe end of the pure alexia spectrum (patients whose reading times are in the order of seconds).

If the generalised visual impairment hypothesis for pure alexia is correct, then a number of key question emerge including: (a) what is the critical nature of the patients' visual impairment and (b) why are words – over and above other visual objects – so vulnerable to this impairment? Answering these questions will necessitate further patient investigations but the present study was motivated to utilise visual distortion in normal participants to provide important convergent evidence. Specifically, we sought (a) to provide additional demonstrations that general visual distortions lead to length effects in reading times of normal participants; and (b) to investigate which types of visual distortion succeed or fail in inducing such length effects. Understanding which types of visual distortion induce length effects will give us important clues about which aspects of visual processing (e.g., perceptual, spatial, attention and top-down feedback) are critical to word recognition.

If words are considered purely in terms of their visual properties then they have some rather atypical characteristics: (i) they can be considered, simultaneously, at two levels of analysis: letters or whole words; (ii) each element is differentially important in their forward role in reading – for letter-based languages, each letter provides important information for phonological activation while the whole word (the specific combination and order of letters) is critical in word identification and meaning; (iii) the elements (letters) are small, complex, highly similar visual objects that appear repeatedly across and sometimes within a word; (iv) despite these visual challenges, word recognition in adult readers is both rapid and accurate. With these factors in mind, we explored different types of visual distortion – manipulations that tend to preserve global shape but impair letter identity (e.g., blurring) versus those that maintain identity but perturb the word Gestalt or shape (e.g., letter size).

**Experiment 1**

The aim of the first experiment was to determine the impact of three types of visual distortion: blurring - that leaves the global word shape intact but affects the discriminability of individual letters; alternating font-size - that affects global word shape but retains individual letter shape; and mirrored print - that forces subjects to engage a novel reading strategy. While mirror-reversal forces naïve participants to use a letter-by-letter strategy to decode word identity, by itself, mirror reversal is probably not a good model of pure alexia in that eye-movements, letter orientation, etc. do not match standard reading conditions.

Verbal response times and error-rates for the visually distorted stimuli were compared to a normal reading condition. We used a within-subjects experimental design to avoid any issues with regard to lexical variables and also to allow a direct comparison between the visually distorted and normal viewing conditions.

*Methods*

*Participants*

All participants were members of the School of Psychological Sciences or members of a volunteer panel who were paid £5 for taking part in the study. All had normal or corrected-to-normal vision and English was their first language. None had a history of developmental dyslexia or of brain injury. This was the case for all the experiments presented here. Twentynine participants, 11 males and 18 females, aged between 17 and 58 years of age (mean age = 21.2 years) took part.

*Materials*

Four lists of 120 words were generated, each comprising 40 matched, word triplets of three, five and seven letters. N-Watch software (Davis, 2005) was used to obtain CELEX written frequencies (Baayan *et al.*, 1995). For each word length, 20 words were high-frequency items (mean written frequency of 113.4 occurrences per million) and 20 were low-frequency items (mean written frequency of 1.9 occurrences per million). Mean written frequency was matched across the four word lists.

*Figure 1 about here*

The four stimulus conditions (*normal* font, *blurred word*, *alternating* font-size and *mirrored* words) were generated using Matlab (MathWorks, 1998). All stimuli were lowercase, black, Arial font, displayed on a white background. Examples of each stimulus type are shown in Figure 1 (first column). Blurred words were created by applying a low-pass Gaussian frequency filter (with a standard deviation of 2.24 cycles per letter) to the frequency-domain transform of the word stimuli (cf. Majaj *et al.*, 2002).

Alternating font-size stimuli were created using 88pt and 40pt font-size The three-letter words subtended the same visual angle as the three-letter words in the normal condition (on average 2.3° ) while the five- and seven-letter words were smaller than in the normal condition (3.7° for five-letter words and 5.0° for seven-letter words, maximum visual angle < 6.6°) so that any length effect observed could not be attributed to an increase in physical size of the stimuli. The first letter was always in the larger font. The individual letters were horizontally aligned by the mid-point of the *x*-height. For the *normal*, *blurred* and *mirrored* word conditions, the font size was set at 72 pt which meant the stimuli subtended visual angles, on average, of 2.2° for three-letter words, 3.8° for five-letter words and 5.3° for seven-letter words (maximum visual angle < 7°).

Mirrored word stimuli were created by mirror-reversing the individual letters and also the ordering of the letters. All of the stimuli were generated as bitmaps of equal size to avoid any confound of the length of the word on generation and display times of the hardware being used.

*Procedure*

Stimulus presentation was controlled by E-Prime software (Psychology Software Tools, Pittsburgh, PA, 2002) running on an IBM Pentium III, 1.2GHz computer and displayed on a 15″ SVGA LCD monitor. The participants were seated approximately 100cm from the monitor. Verbal response times were measured using a microphone voice trigger with the E-Prime response box, which recorded the time interval between the onset of the word and the start of a verbal response.

The lists were presented in separate blocks, each comprising one of the stimulus conditions. The assignment of the word lists to the stimulus conditions and the order in which they were presented, were counterbalanced across participants. Each participant carried out 10 practice trials before the start of the experimental block to familiarise themselves with the appearance of the stimuli.

At the start of each trial, a fixation cross was displayed centrally for 1250ms. This was then replaced with the word stimulus which remained on the screen until the participant triggered the voice key with a verbal response. The experimenter initiated the start of the each trial. The participants were instructed to read the word aloud as quickly and as accurately as possible. All response-errors were noted and the sessions were audio recorded.

*Results*

*General analysis*

The extent of the reading impairment in LBL reading is usually described in terms of the slope for the word-length effect and is expressed as an increase in reaction time as a function of the number of letters (milliseconds per additional letter). For the reaction time (RT) analysis, incorrect and null responses were omitted. Voice key mis-triggers (2.9% of trials) and trials with RTs greater than ±3 standard deviations from each participant's mean for a given condition and word-length were also removed (1.8% of trials). Table 1 shows the mean correct verbal RTs for reading three-, five- and seven-letter words for the four stimulus conditions.

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Table 1 about here

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Repeated measures ANOVAs on the by-subject ($F_1$) and by-item ($F_2$) means were conducted. Condition (normal, blurred, case and mirror), word length (three, five and seven) and frequency (high and low) were all within-subject factors. Word length and lexical frequency were between-subject factors in the by-items analysis. There were significant main effects for condition $F_1(3, 84) = 123.3$, $p < .001$; $F_2(3, 1419) = 1030.6$, $p < .001$, word-length $F_1(2, 56) = 58.0$, $p < .001$; $F_2(2, 473) = 66.4$, $p < .001$ and frequency $F_1(1, 28) = 93.6$, $p < .001$; $F_2(1, 473) = 61.8$, $p < .001$. There was no significant three-way interaction in the by-subjects analysis $F_1$(6,

168) = 1.31, $p$ = .254 although this was significant in the by-items analysis, $F_2(6, 1419) = 2.583$, $p$ =.017.

*Effects of condition and word length*

There was a strong interaction between condition and word length, $F_1(6, 168) = 41.8$, $p <$ .001; $F_2(6, 1419) = 47.5$, $p < .001$, originating largely from the mirrored word condition (see Table 1). However, even with the data for the mirrored condition removed, the interaction remained significant, $F_1(4, 112) = 13.9$, $p < .001$; $F_2(4, 948) = 6.93$, $p < .001$.

*Figure 2 - about here*

The central issue to this study was whether visual distortions could provoke increased effects of word length in reading in normal subjects. ANOVAs were performed to compare the mean of each condition with the mean from the normal condition (see Figure 2). There was no significant main effect of blurring (Figure 2a), $F_1(1, 28) = 2.6$, $p = .117$; $F_2(1, 474) = 15.5$, $p <$ .001, but significant effects were found for both the alternating font-size (Figure 2b), $F_1(1, 28) =$ 14.3, $p = .001$, $F_2(1, 474) = 90.3$, $p < .001$, and mirrored word conditions (Figure 2c), $F_1(1, 28) =$ 128.7, $p < .001$; $F_2(1, 473) = 1086.6$, $p <$ . 001. There was a similar pattern for the interaction of condition and word-length, with no interaction for the blurred words, $F_1(2, 56) = 0.47$, $p = .627$; $F_2(2, 474) = 0.34$, $p < .712$, but significant interactions of word length with both alternating font-size, $F_1(2, 56) = 18.4$, $p < .001$; $F_2(2, 474) = 13.2$, $p < .001$, and mirrored words, $F_1(2, 56) =$ 43.4, $p < .001$; $F_2(2, 474) = 50.1$, $p < .001$. The slopes of the word-length effects for the conditions were 7.0 msec/letter for the normal condition; 6.6 msec/letter for blurred words; 17.1 msec/letter, alternating case; and 222.8 msec/letter for the mirrored word condition.

*Effects of condition and lexical frequency*

The simple main effect of frequency was consistent across all conditions, a highly reliable finding (Forster & Chambers, 1973). The more important question was whether the pattern of interaction of condition and frequency ($F_1(3, 84) = 43.3$, $p < .001$; $F_2(3, 1419) = 29.4$, $p < .001$) reflected that for condition and word length. An ANOVA did, indeed, again show no interaction for blurred words $F_1(1, 28) = 0.33$, $p = .568$; $F_2(1, 474) = 0.53$, $p < .817$, in contrast with significant interaction effects for the alternating case [$F_1(1, 28) = 12.8$, $p = .001$; $F_2(1, 474) = 13.5$, $p < .00$], and mirrored conditions [$F_1(1, 28) = 43.7$, $p < .001$; $F_2(1, 474) = 31.3$, $p < .001$].

*Error analysis*

The error rates for each condition were: for normal, 0.44%; blurred, 1.11%; alternating case, 0.61%; mirrored, 10.23%. Of the incorrect responses, 73.7% were visual errors, in which participants generated an alternative word which contained at least 50% of the letters from the target word (e.g., SCREE → “scream”); 21.8% were non-word errors which also contained at least 50% of the target word letters (e.g., SWIPE → “sweak”); and 2.6% were phonological errors (e.g., AUDIT → “orbit”). These categories accounted for 98.1% of the total errors. Only two errors were classified as semantic errors (e.g., QUACK → “duck”, and PLATE → “glass”) but even these responses share some of the same letters with the target word, emphasising the visual rather than semantic nature of the errors produced. LBL patients have been noted, in the main, to make errors which are real words that differ visually from the target (Cummings et a., 2006).

A repeated measures ANOVA was conducted on the error rates, including both incorrect and null responses, collapsed across frequency to increase statistical power, with condition (normal, blurred, alternating and mirrored) as a within subjects factor and word-length (three-, five- and seven-letters) as a within-subjects and between-items factor. There was an effect of condition, $F_1(3, 84) = 54.1$, $p < .001$; $F_2(3, 1431) = 145.1$, $p < .001$, but not of length $F_1(2, 56) = 0.151$, $p = .860$; $F_2(2, 477) = 0.94$, $p < .910$, and there was also no interaction between these two variables, $F_1(6, 168) = 0.354$, $p = .907$; $F_2(6, 1431) = 0.243$, $p = .962$. The greatest number of errors was seen in the mirrored condition for which null responses increased with word length (three-letters, 6%; five-letters, 32.7%; and seven-letters, 61.2%), while incorrect responses showed the opposite trend (three-letters, 46.3%; five-letters, 32.3%; seven-letters, 21.3%).

*Summary*

We found a significant word-length effect when normal subjects read words distorted by alternating font-size and by mirroring words but not after blurring (though see Experiment 2). The dramatic effect of mirror-reversing reflects the fact that this condition explicitly demands a LBL reading strategy to identify each letter in turn (see Introduction). The comparison of greatest interest here, therefore, is that between alternating font-size and blurring. Whereas alternating font size manipulates the global word shape while leaving the individual letter forms unchanged, the blurred condition distorts the individual letters whilst leaving the global shape intact. These initial results suggested that it may be a distortion to the global, rather than local, word shape that underlies the word-length effect. Experiment 2 addressed this possibility.

We also found an interaction between lexical frequency and condition. The visual distortions that led to an effect of word-length (i.e., alternating and mirrored stimuli) showed an increased effect of frequency, which has been demonstrated previously in normal subjects (Ellis, 2004; Young & Ellis, 1985). This is important to note: the impairment causing LBL reading not only induces a pathological length effect but also increases the frequency effect, and both effects arise in simulations of LBL reading (Behrmann et al., 1998b). Inducing increased length and frequency effects underline, therefore, the potential of this experiment method for mimicking the core features of LBL.

**Experiment 2**

In Experiment 1 we found that alternating font-size caused an increased word-length effect whereas blurring did not. In the alternating font-size condition the global shape of the word is distorted but the quality of the individual letters remains unaffected; this pattern is reversed for the blurred words. While this distinction might prove important in understanding the critical nature of the underlying visual impairment in pure alexia, it is also possible that the null result for blurring reflected the application of insufficient distortion. It seems reasonable to assume that the normal visual system has a degree of tolerance for distortions or sub-optimal viewing conditions that occur in everyday life. In the second experiment, therefore, we varied the degree of blurring in a graded manner to investigate the hypothesis that a length effect would emerge but only at sufficient degrees of distortion.

*Methods*

*Participants*

Twenty-four participants, 13 females and 11 males, aged between 20 and 51 years of age (mean age = 29.5 years) took part in Experiment 2.

*Materials*

Four lists of 75 words each were used. Each list comprised 25 matched triplets of low-frequency words (minimum 0.8 occurrences per million, maximum 21.6 occurrences per million). Each triplet consisted of a three-, five- and seven-letter word matched for written frequency and for the initial phoneme. Three levels of spatial-frequency distortion were compared to normal print. The stimuli were created by applying a low-pass Gaussian filter to the frequency-domain transform of the word stimuli. The levels of Gaussian filter had standard deviations of 0.55, 0.62 and 1 cycles per letter.

*Procedure*

Each of the four word lists was assigned to one of the stimulus distortion conditions (*normal*, *level1*, *level2*, *level3*) and presented in randomised block of 300 words. The word-list and stimulus condition assignment was counterbalanced across participants. Each participant carried out 10 practice items at the start of the experiment.

*Results*

For the RT analysis 2.9% of trials were removed because of voice trigger problems and a further 1.7% were removed because the RTs were greater than ±3 standard deviations from the participant's mean for the condition and word-length. Figure 3 shows the mean correct reading latencies for three-, five- and seven-letter words for the four stimulus conditions.

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Figure 3 about here

Repeated measures ANOVAs on the by-subject ($F_1$) and by-item ($F_2$) means were conducted for the trials with correct responses (see below for the error analysis). Condition (normal, level l, level 2 and level 3) and word length (three-, five- and seven-letters) variables were all within-subject factors, except for word length in the by-items analysis which was a non-repeated factor. There were significant main effects for condition $F_1(3, 69) = 78.0$, $p < .001$; $F_2(3, 858) = 290.7$, $p < .001$, and length, $F_1(2, 46) = 5.34$, $p = .008$; $F_2(2, 286) = 6.08$, $p = .003$. There was also a significant interaction between condition and length, $F_1(6, 138) = 3.11$, $p = .007$; $F_2(6, 858) = 3.47$, $p = .002$ for the overall group analysis.

To analyse the origin of the interaction, the individual effects of each level of blurring was compared to the normal condition by ANOVA. There was an effect of condition for all levels of blurring; level 1, $F_1(1, 23) = 90.1$, $p < .001$; $F_2(1, 297) = 133.6$, $p < .001$; level 2, $F_1(1, 23) = 76.6$, $p < .001$; $F_2(1, 295) = 441.8$, $p < .001$; level 3, $F_1(1, 23) = 88.4$, $p < .001$; $F_2(1, 288) = 372.6$, $p < .001$. Importantly, there was an interaction for the greatest level of blurring, $F_1(2, 46) = 3.59$, $p = .035$; $F_2(2, 288) = 4.43$, $p = .013$ but no significant interaction between condition and length for level 1 blurring, $F_1(2, 46) = 0.413$, $p = .664$; $F_2(2, 297) = 0.535$, $p = .586$ or level 2 blurring $F_1(2, 46) = 0.861$, $p = .429$; $F_2(2, 295) = 1.79$, $p = .169$ (see Figure 3). The slope of the length effect increased as a function of the level of blurring; normal - 8.9 msec/letter; level 1 - 10.6 msec/letter; level 2 - 15.6 msec/letter; and level 3 - 75.7 msec/letter.

*Error analysis*

The number of errors also increased with the level of distortion; for the normal - 0.7%; level 1 - 1.2%; level 2 - 13.6%; level 3 - 29.1%. Out of the errors made, 68.9% were visual identification errors in which participants generated an alternative word which contained at least 50% or more of the letters from the target word (e.g., BLOND → “blend”); only 0.6% were non-word errors which also contained 50% of the target word letters (e.g., PROBATE → “probla”); 25.5% were unrelated errors, which were defined as real word responses with less than 50% of the letters from the target word (e.g., PEASANT → “yawning”); and 2.3% were semantic errors (e.g., FURNACE → “thermos”, SAP → “tulip”, BUTCHER → “torture”) with the vast majority of these errors occurring to the longer words (3-letter words, 6.7%; 5-letter words, 20.0%; 7-letter words, 73.3%).

A repeated measures ANOVA was conducted on the error rate, collapsed across frequency to increase statistical power, with condition (level of blurring) as a within subjects factor and word-length (three-, five- and seven-letters) as within-subject and between-item factors. There was an effect of condition, $F_1(3, 69) = 91.7$, $p < .001$; $F_2(3, 891) = 2111.7$, $p < .001$, but no effect of length $F_1(2, 46) = 0.690$, $p = .507$; $F_2(2, 297) = 0.423$, $p < .656$, and there was also no interaction between these two variables, $F_1(6, 168) = 0.357$, $p = .905$; $F_2(2, 297) = 0.627$, $p = .535$. Further investigation suggested that this pattern varied according to error type: null responses increased as a function of word length (3-letter words - 21.4%; 5-letter words - 33.3%; and 7-letter word - 45.3%) while incorrect responses showed the opposite trend (3-letter words - 36.7%; 5-letter words - 34.3%; and 7-letter word - 29.0%).

**General Discussion**

One set of theories suggests that reading is based upon general, ontogenetically earlier neural mechanisms (the "primary systems hypothesis": Patterson & Lambon Ralph, 1999) and that, more specifically, pure alexia reflects damage to generalised visual processing rather than a reading-specific recognition system (Behrmann et al., 1997). If the generalised visual impairment hypothesis for pure alexia is correct, then a number of key questions emerge including what are the critical characteristics of the patients' visual impairment? While this question needs to be addressed by further investigation of pure alexic patients, the present study sought to utilise the impact of visual distortion on reading in normal participants to provide convergent evidence for this approach. Specifically, we sought (a) to provide additional demonstrations that visual distortion induces length effects in reading times of normal participants and (b) to investigate which types of visual distortion succeed or fail in inducing such length effects – thereby giving some indication as to the critical nature of the visual impairment that underpins pure alexia.

We found that disruption to both global word shape (alternating font-size, Experiment 1) and reduction of the distinctiveness of local components (blurring, Experiment 2) both induced a significant word-length effect. In addition, substantial length effects follow when words are mirror-reversed. The data also indicate that the length effect may only emerge once a sufficient degree of distortion is applied – confirming that the normal visual system has some tolerance to non-optimal viewing conditions as one might expect from the variation found in everyday visual environments. When pure alexic LBL readers make errors they are commonly close, visually-related responses (Behrmann, Plaut, & Nelson, 1998; Patterson & Kay, 1982). This second aspect of their behaviour (in addition to the length effect) was also captured in these two experiments; alterations of word shape or letter distinctiveness led to a majority of visually-related errors in these normal participants.

This study adds to the increasing body of evidence that different kinds of visual distortion can provoke a word length effect in normal subjects. The list includes changes in contrast level (Nelson, Behrmann & Plaut, 1999), manipulation of letter confusability and spatial frequency filtering (Fiset et al. 2006 a and b) and - in our study - case alternation, blurring and mirror-reversal. The fact that a variety of stimulus distortions produce the effect suggests that word-length is not a pathognomonic symptom, but rather the emergent effect of a number of different kinds of deficit of which degraded visual input is one. This notion has been taken a further step by Braet & Humphreys (2006) who argue that different brain regions are recruited to deal with different kinds of visual challenge: occipital lobes for contrast reduction, parietal lobes for case alternation.

Additional support for this viewpoint derives from the growing evidence that a variety of different patient groups exhibit length effects in reading. These include patients with parietal lesions (Warrington & Shallice, 1979) as well as those with right hemifield loss (hemianopic alexics: Leff *et al*., 2001). The patient groups also include an unexpected source: recent findings that patients with semantic dementia (SD) also show small but abnormal word-length effects (Cumming *et al.*, 2006; Gold *et al.*, 2005). SD patients are not, on the whole, liable to deficits in visual processing but do have degraded semantic knowledge. In addition, the progressive atrophy that causes this condition is focused upon the anterolateral aspects of the temporal lobes, bilaterally and not upon the occipitotemporal region implicated in pure alexia (Williams *et al.*, 2005). Word knowledge from the semantic system would normally assist in the parallel process of word recognition by providing important top-down support (as per the word recognition model:(Behrmann *et al*., 1998b; Rumelheart & McClelland, 1982). Indeed, lexical decision has been shown to be reliant upon the integrity of word meaning in semantic dementia (Patterson *et al*., 2006; Rogers *et al*., 2004). In semantic dementia, therefore, the word-length effect is thought to be due to diminished top-down influence from the damaged semantic system to orthography (Cumming *et al*., 2006).

In conclusion, it would appear that a variety of visual distortions and a number of disparate neurological conditions induce word length effects in reading. This emergent theme has important implications for the study of letter-by-letter reading and pure alexia – 'letter-by-letter' reading ceases to be a useful way of defining patients with alexia resulting from degraded visual input. In addition, it is possible that variation found in the letter-by-letter literature (e.g., alexia with and without hemianopia; alexia with and without impaired number recognition; alexia with and without generalised visual impairment) may reflect, at least in part, the amalgamation of disparate patient groups with different sites of neurological damage.

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**Tables**

*Table 1*

*Mean reading times from Experiment 1 for three-, five- and seven-letter words for each stimulus condition, collapsed across frequency (standard deviation in parenthesis).*

| Word length | Normal | Alternating | Blurred | Mirrored |
|---|---|---|---|---|
| 3 letters | 520.5<br>(78.7) | 530.3<br>(76.1) | 530.9<br>(83.0) | 1318.3<br>(513.4) |
| 5 letters | 516.1<br>(70.5) | 546.8<br>(84.6) | 530.3<br>(86.0) | 1672.6<br>(482.9) |
| 7 letters | 548.5<br>(78.5) | 596.4<br>(97.4) | 557.2<br>(89.9) | 2209.3<br>(874.7) |

**Figures**

*Figure 1: example stimuli from Experiments 1 & 2*

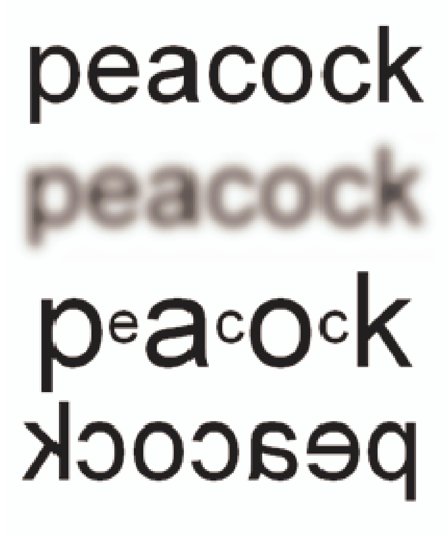
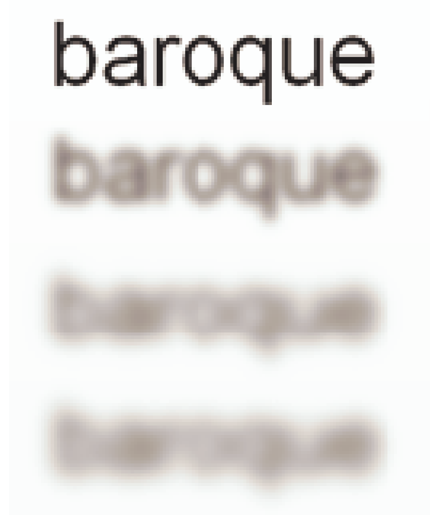
<table>
<tr><th>Experiment 1</th><th>Experiment 2</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

*Figure 2a*

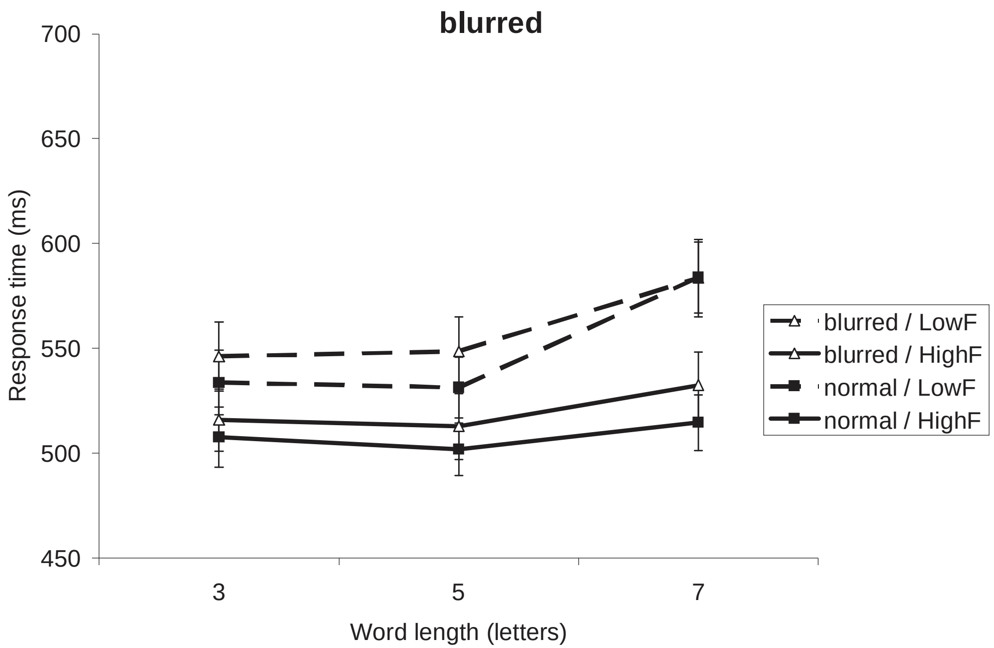

blurred
700
650
600
550
500
450
Response time (ms)
3
5
7
Word length (letters)
blurred / LowF
blurred / HighF
normal / LowF
normal / HighF

Figure 2b

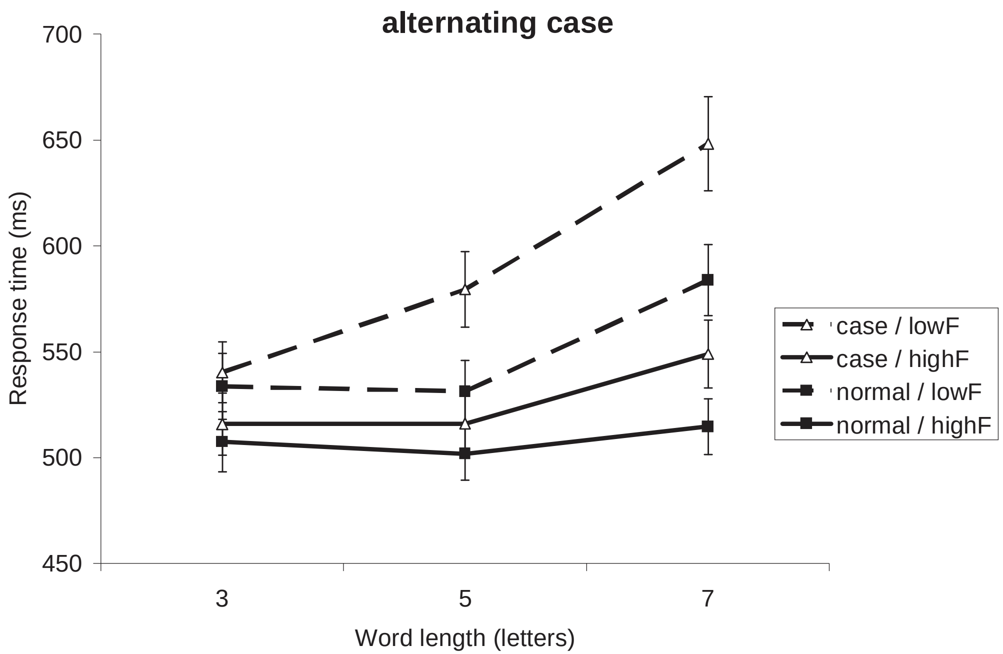
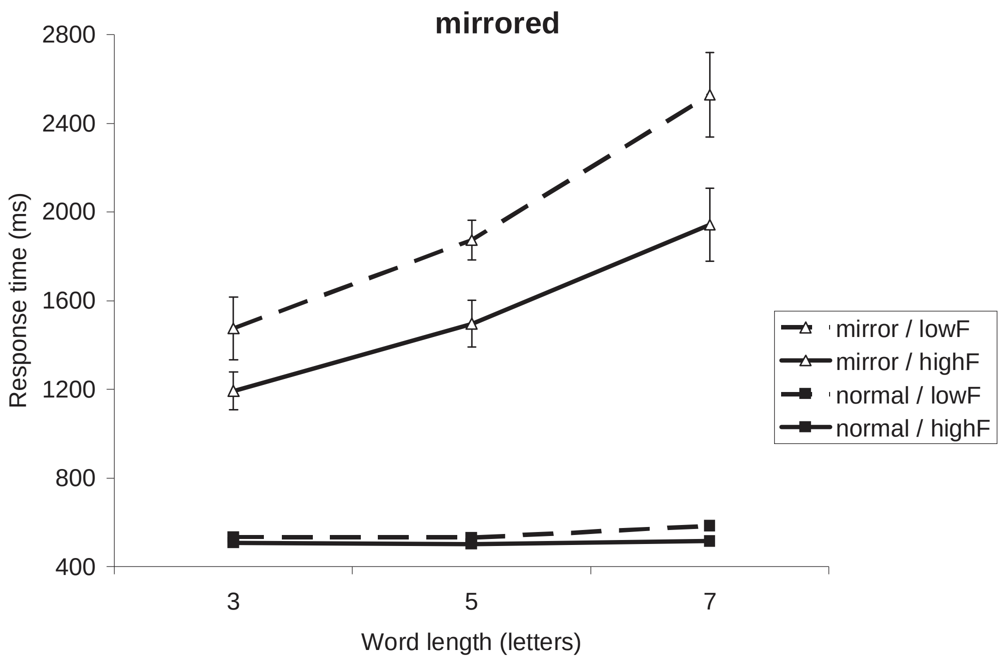
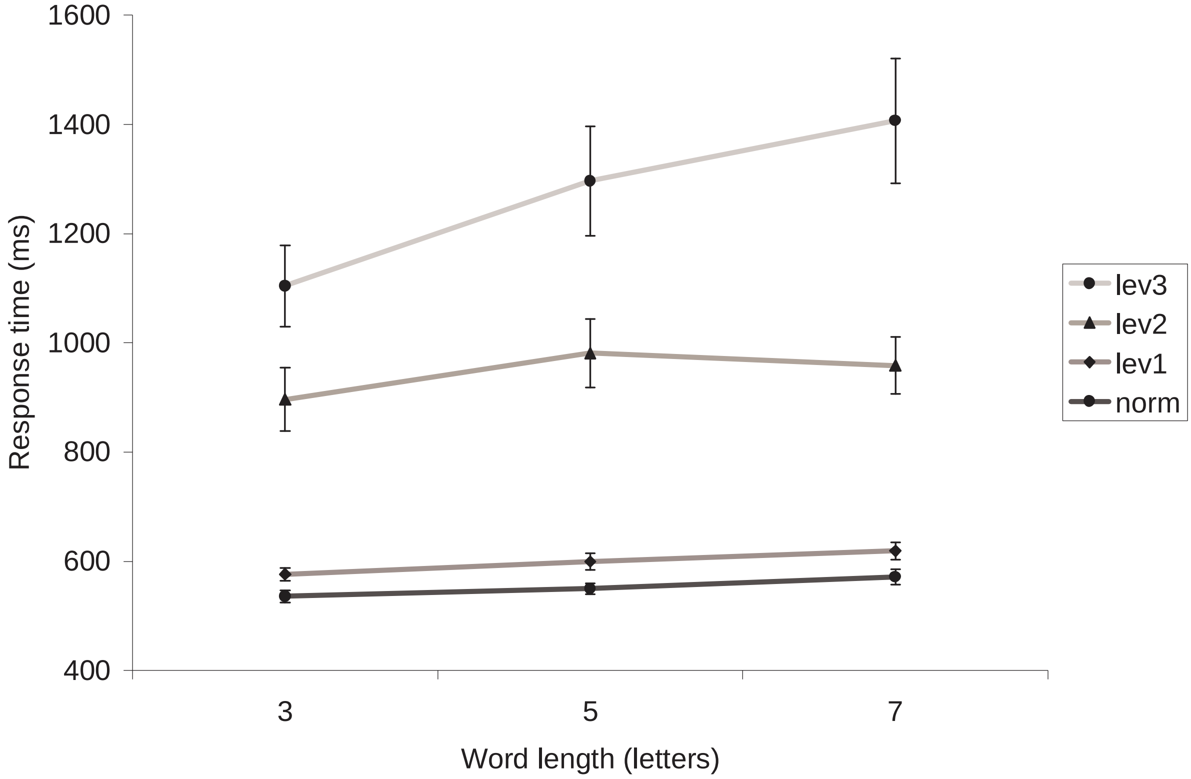

alternating case
700
650
600
550
500
450
Response time (ms)
3
5
7
Word length (letters)
case / lowF
case / highF
normal / lowF
normal / highF

Figure 2c



mirrored
2800
2400
2000
1600
1200
800
400
Response time (ms)
3
5
7
Word length (letters)
mirror / lowF
mirror / highF
normal / lowF
normal / highF

Figure 3


1600
1400
1200
1000
800
600
400
Response time (ms)
3
5
7
Word length (letters)
lev3
lev2
lev1
norm