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From word superiority to word inferiority: Visual processing of letters and words in pure alexia

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Visual processing and naming of individual letters and short words were investigated in four patients with pure alexia. To test processing at different levels, the same stimuli were studied across a naming task and a visual perception task. The normal word superiority effect was eliminated in both tasks for all patients, and this pattern was more pronounced in the more severely affected patients. The relationship between performance with single letters and words was, however, not straightforward: One patient performed within the normal range on the letter perception task, while being severely impaired in letter naming and word processing, and performance with letters and words was dissociated in all four patients, with word reading being more severely impaired than letter recognition. This suggests that the word reading deficit in pure alexia may not be reduced to an impairment in single letter perception.

Keywords: Letter-by-letter reading; Letter perception; Word length effect; Word reading.

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Pure alexia is an acquired reading disorder characterized by slow and effortful reading in the absence of deficits in writing, spelling, and other language functions. Pure alexia typically arises following a lesion in ventral occipitotemporal areas in the left hemisphere and may be specifically related to damage in the midfusiform gyrus (the “visual word form area”, e.g., Cohen et al., 2003; Leff, Spitsyna, Plant, & Wise, 2006). Most patients with pure alexia read words correctly, but show elevated response times compared to normal readers. One of the main symptoms of pure alexia is the word length effect (WLE), an approximately linear relationship between the number of letters in a word and the time taken to read it. The WLE is often taken as an indication of a serial letter-by-letter reading process (e.g., Rayner & Johnson, 2005), which stands in contrast to the parallel processing of letters in words that is characteristic of normal reading (Adelman, Marquis, & Sabatos-DeVito, 2010; Weekes, 1997).

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A central question in pure alexia research concerns the nature of the cognitive impairment that makes letter-by-letter processing necessary for the patients to be able to read. Commonly the WLE is interpreted as reflecting a deficit in parallel letter processing. An impairment even in single letter processing (perhaps attributable to an even more fundamental deficit in visual perception) is, however, also thought to be critical in pure alexia (Behrmann, Plaut, & Nelson, 1998).

Given that pure alexia is mainly reflected in response times (RTs), while reading accuracy may be within normal limits, RTs have been central in experimental studies of this disorder, and some evidence suggests that RTs increase systematically also for other visual stimuli than words (Mycroft, Behrmann, & Kay, 2009). Aiming to characterize the proposed visual deficit in pure alexia, we have previously relied on accuracy-based experiments with limited stimulus exposure (Starrfelt, Habekost, & Gerlach, 2010; Starrfelt, Habekost, & Leff, 2009) and analyses based on a theory of visual attention (TVA; Bundesen, 1990; Bundesen, Habekost, & Kyllingsbæk, 2005), which allows several parameters of visual processing to be derived from a single experimental task (see Habekost & Starrfelt, 2009, for further details). In these studies, we have found marked reductions in both visual processing speed and the storage capacity of visual short-term memory for letters as well as digits in patients with pure alexia (Starrfelt, Habekost, & Gerlach, 2010; Starrfelt, Habekost, & Leff, 2009). Based on these findings, and the premise that fluent reading is a very visually demanding process, we have suggested that the reductions in basic visual processing capacity might explain the slow reading and the WLE observed in pure alexia. We have subsequently attempted to link the reduced visual span and speed for single letters and unrelated stimuli directly to performance with words (Starrfelt, Gerlach, Habekost, & Leff, 2013; Starrfelt, Habekost, & Gerlach, 2010) by investigating the *word superiority effect* (WSE). The WSE refers to the phenomenon that normal readers are better at identifying letters embedded in words than in letter strings, or even single letters. The effect is typically found in experiments where stimuli are presented briefly and then masked, followed by either a forced choice or a free report task. Typical word superiority experiments use words and nonwords as stimuli (see Johnston, 1981; McClelland & Rumelhart, 1981), but the effect may also be found when comparing performance with words to performance with single letters (Jordan & Bevan, 1994; Starrfelt, Petersen, & Vangkilde, 2013).

In one pure alexic patient (N.N., Starrfelt, Habekost, & Gerlach, 2010), we found an impairment in reporting letters from both words and nonwords, and no WSE, indicating that the patient's reduced processing speed and visual span indeed affected his performance with letters in words. In four other patients, however, we failed to find this pattern. Although they were all impaired in reporting letters from both words and nonwords, they all performed better with words than nonwords, and the size of their WSE was systematically related to their visual field defect rather than the severity of their alexia (Starrfelt, Gerlach, et al., 2013). In all five patients, however, we obtained evidence that although visual processing of letters in words and nonwords was abnormal, the patients' abilities for parallel letter processing were not completely abolished.

The focus of this paper is on the relationship between letter identification and word reading in pure alexia, investigated in two experiments tapping overt naming and visual perception of the same set of letters and words. Using the same tasks and stimuli with normal readers, we have recently shown that the WSE can be revealed both in the naming and in the perception task (Starrfelt, Petersen, & Vangkilde, 2013). With the present study we investigate whether the word superiority effect is eliminated or reversed in patients with pure alexia, and whether abnormal performance is differentially reflected in the naming task or the perceptual (accuracy-based) task. Our investigation is divided into two parts: Study 1 is an initial case study of a Danish patient with a relatively mild pure alexia. Study 2 is a follow-up study of three additional patients, all of whom have more severe pure alexia. For Study 2, the experimental paradigms were adapted to English.

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GENERAL METHOD

Statistical tests for deficits and dissociations

The experiments we report compare performance on two types of stimuli—letters and words—in two different experiments: a naming task (1A and 2A), with RT as the dependent measure, and a visual perception task with masked exposure (1B and 2B) with accuracy across exposure duration as the dependent measure. We are interested in the patients' performance on the individual tasks (whether they are impaired or not), but, importantly, we also want to know whether the patients show a different pattern of performance with letters and words, compared to controls (i.e., whether they show a dissociation between tasks). To test for specific deficits in patient performance, we apply the t-test devised by Crawford and Howell (1998; Crawford & Garthwaite, 2002). This test allows the comparison of the mean score of a single patient to the distribution of mean scores in the control group and has been shown to be robust even with small control samples. In addition, we apply related statistical tests devised to detect and evaluate dissociations in patient performance, relying on the operational criteria for dissociations suggested by Crawford and colleagues (e.g., Crawford & Garthwaite, 2005, 2007; Crawford, Garthwaite, & Gray, 2003). These criteria provide a statistically precise definition of the distinction between classical and strong dissociations originally suggested by Shallice (1988). In order to conclude that there is a (putatively) classical dissociation, the patient's score should differ significantly from that of the control group on one of two tasks, evaluated by Crawford and Howell's t-test, while performance should be within the normal range on the other task, and—importantly—the difference between the patient's standardized scores in the two tasks should be significant. For the less stringent strong dissociation, there should be a significant difference between the patient's standardized scores as compared to the control group on the two tasks in question, while both scores may differ significantly from the mean of the control group—that is, the patient is impaired in both tasks, but significantly more so in one than the other.

In the current context, the relation to normal data is very important, as should be clear when considering the phenomenon we are investigating: the word superiority effect (or word-letter effect). When the normal pattern is that one task is performed markedly better than another, then equal performance in the two tasks in a patient—for example, in terms of RT—could be considered abnormal (see Laws, 2005). Crawford's methods allows us to test whether the difference (or lack thereof) between two test scores is abnormal, and the p-value provides an estimate of how probable it is that the same pattern of performance could be observed in the control group.

Unless otherwise specified, all tests of deficits and dissociations in this paper are one-tailed due to a directional hypothesis (i.e., the patient's performance should be poorer than control participants' performance, or performance with words should be poorer than that with letters). Statistical tests of performance with letters versus words in the control groups are also performed one-tailed, based on predictions from previous studies of normal participants.

TVA-based data modelling

The theory of visual attention (TVA) is a mathematical model of visual capacity and selectivity that accounts for a wide range of findings on visual attention (see Bundesen, 1990; Bundesen & Habekost, 2008). TVA offers a set of specific functional parameters for the analysis of performance on simple visual tasks. Two of these parameters are of special interest in the present investigation: the speed of visual processing C and the perceptual threshold t_0. A single item report experiment is the most direct way to estimate individual values of these two parameters for a given type of object (e.g., a letter). In this paradigm, an object is shown at the centre of fixation, and the stimulus display is followed by a pattern mask to erase the visual afterimage. The task is to verbally report (unspeeded) the identity of the object. Exposure durations are varied to cover the range from the participant's perception threshold to

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near-ceiling performance. Given this experimental procedure, performance (mean number of correct reports) develops characteristically as a function of the exposure duration. When the exposure time is shorter than the participant's perception threshold, t_0, the score is zero. After the threshold has been reached, the score rises abruptly. The slope of the curve at the point where the exposure time equals t_0 corresponds to the participant's processing speed, C. As such, C serves as a measure of the efficiency of visual form recognition. The performance curve eventually levels off to asymptotically approach the exposure duration where the participant can invariably perceive the item. Assuming a particular C and t_0 value, one can calculate the probability that the object is encoded at any exposure time (see Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011; Kyllingsbæk, 2006, for details). This implies that for a given individual, one can estimate the C and t_0 values that maximize the probability of obtaining the total set of observed data (all trials in the experiment). In our study, the individual data from TVA-based assessment were fitted by a maximum likelihood fitting procedure using the LibTVA toolbox for MatLab by Dyrholm et al. (2011).

STUDY 1: PATIENT L.K.

Case description

Patient L.K. is a right-handed woman (Edinburgh Handedness Inventory quotient LQ+ 100; Oldfield, 1971) who was 29 years old at the time of the present investigation (November 2011). In 2008 she suffered a haemorrhage affecting occipitotemporal areas in the left hemisphere. The haematoma was surgically evacuated, and she recovered well apart from persistent reading problems and a right-sided hemianopia. With extensive use of computerized reading equipment, she has now finished her education (her Master's thesis received the highest possible grade), and, in spite of her reading problems, she is now pursuing an academic career.

A magnetic resonance imaging (MRI) scan from September 2011 (see Figure 1) shows a left posterior lesion affecting the lateral and inferior occipital cortex, as well as the lateral part of the fusiform gyrus, the lateral occipitotemporal sulcus, and the inferior temporal gyrus. The mid portion of the fusiform gyrus is spared, but the white matter above it is affected.

Background testing

In 2009–2010, preliminary testing revealed that L.K. showed elevated reaction times (RTs) in word reading and a significant WLE (419 ms per letter in 2010), as well as slow and effortful text reading. She made very few reading errors. Her writing was flawless, as evidenced by writing sentences and single words (Psycholinguistic Assessments of Language Processing in Aphasia, PALPA, Subtest 31). L.K.'s RTs in picture naming were slightly elevated, while her visual fields were found intact on a computerized perimetry (Kasten, Gothe, Bunzenthal, & Sabel, 1999; see Starrfelt, Nielsen, Habekost, & Andersen, 2013, for details on neuropsychological background tests). L.K. has normal contrast thresholds for detection and discrimination across a wide range of spatial frequencies, indicating that her basic visual functions are unaffected (Starrfelt, Nielsen, et al., 2013).

To measure L.K.'s WLE in the context of the present investigation, she performed a speeded naming task of 150 words consisting of 5, 6, or 7 letters (50 words per word length). The words were written in capital Courier New Font size 40 and were presented in white on a black background in the centre of a computer screen. Compared to her 10 control participants who were matched for age, education, and handedness (see Starrfelt, Nielsen, et al., 2013) L.K.'s overall mean RT (2295 ms, $SD = 821$) was significantly elevated (controls mean RT = 471 ms, $SD = 78$, $t = 22.3$, $p < .001$; Crawford & Howell's test). L.K. showed a significant WLE of 242 ms/letter [$r^2 = .057$, $F(1, 134) = 8.12$, $p < .01$]. The mean WLE for the controls was 9 ms/letter ($SD = 9$), and this effect was significant in three of the

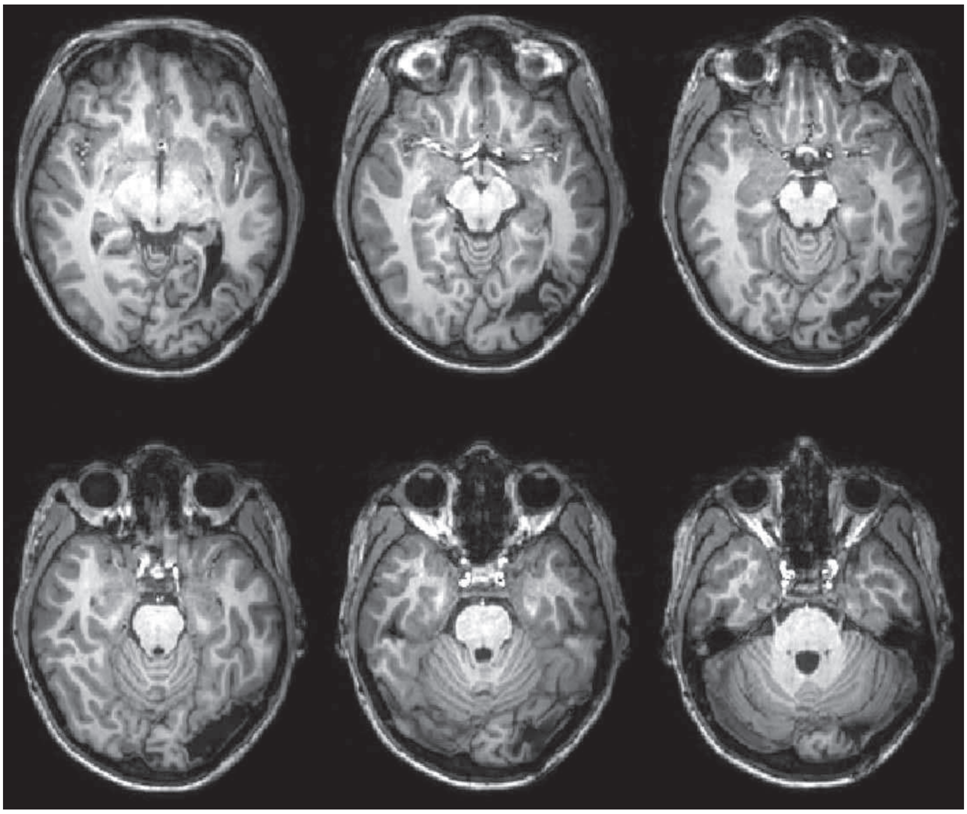

Figure 1. *Magnetic resonance imaging (MRI) scan of patient L.K.'s lesion. Images are presented following radiological convention (left hemisphere depicted on the right).*

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control participants (WLEs of 13 ms/letter, 13 ms/letter, and 19 ms/letter, respectively, all $p < .05$). See Figure 2 for an illustration of L.K.'s RTs and WLE compared to control participants.

Control participants

Experiments 1A and 1B were originally developed in an attempt to test the word superiority effect within the framework of TVA and were run with a sample of undergraduate students (Starrfelt, Petersen, & Vangkilde, 2013). This group consisted of 21 undergraduate students (6 male; mean age 23 years, range 19–36) at the University of Copenhagen, who participated in the study for course credit. As these participants were approximately matched to L.K. for age and education, we have used them as the control group for her performance in these experiments. All controls had normal or corrected-to-normal vision and no history of neurological or psychiatric illness or dyslexia. Both L.K. and the control participants gave informed written consent according to the Helsinki Declaration to participate in the study, and approval was given by the Biomedical Research Ethics Committee in Copenhagen (KF 01–258988). For the control participants, the testing was conducted as part of a larger study that included an additional experiment using the same stimuli and where the order of tasks and stimulus conditions was counterbalanced across subjects. Six control participants performed the single item tasks reported here in the same order as L.K. did.

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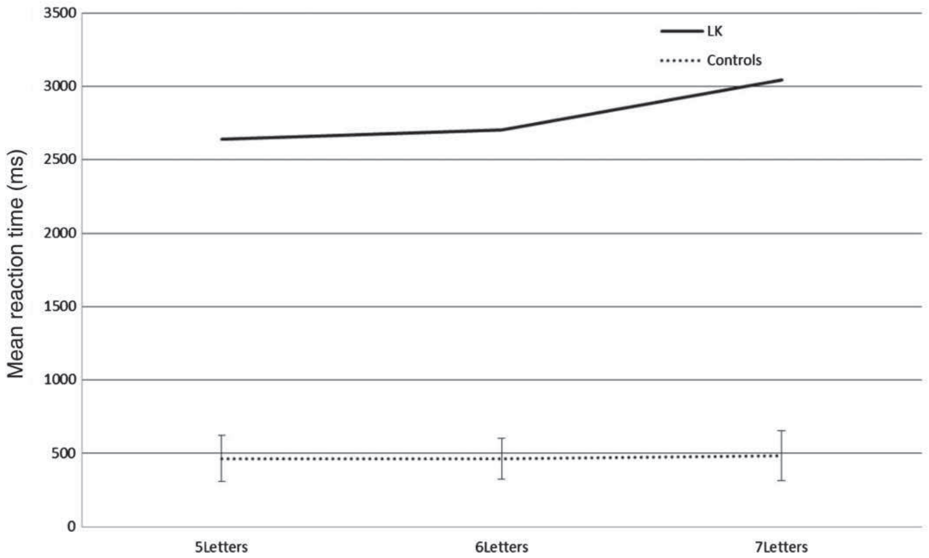

Figure 2. *Word length effect in patient L.K. compared to that in control participants. Reaction time is plotted as a function of word length. Error bars indicate 2 standard deviations from the mean of the controls' RT.*

Stimuli and masks

The same sets of letter and word stimuli were used in both Experiment 1A and Experiment 1B. The letter set consisted of 25 letters of the alphabet (the letter W is commonly excluded when Danes learn to recite the alphabet, and it is the only letter with a two-syllable name; hence, it was excluded from the stimulus set). For the word condition, a set of 25 high-frequency, three-letter words was created. This list included confusable words so that no individual word could be predicted by identifying only one letter, and the word as a whole needed to be processed (e.g., for the word *mad*, the neighbour words *fad*, *mod*, and *man*, differing in the first, second, and third letter position, respectively, were also included in the list. See Appendix for a list of all word stimuli). The stimuli were presented in lowercase Arial font (point size 40) in white on a black background. A printed list of the stimuli (words or letters, depending on the task at hand) was present in front of the subjects during all experiments with that stimulus type, and all subjects were asked to read through this list of stimuli before Experiment 1 was started. Masks were white-on-black pattern masks constructed of letter fragments.

Experiment 1A: Letter and word naming

Method

In Experiment 1A, either a single letter or a three-letter word was to be named (in separate blocks). The stimuli were randomly selected from the set of items described in the previous section and presented at the centre of the screen with an intertrial interval of 1 s from response to the next stimulus. Subjects were instructed to name the stimuli as quickly and as accurately as possible, and RTs were measured using a voice key. Errors were recorded by the experimenter. There were 50 trials in the letter condition and 100 trials in the word condition, as well as 10 practice trials in each condition. This was originally designed as a practice session for Experiment 1B, and the reason for having more trials in the word condition was to make the subjects familiar with the included word stimuli (everyone knows which letters are in the alphabet, but they did not know in advance which words were included in our set of 25). For

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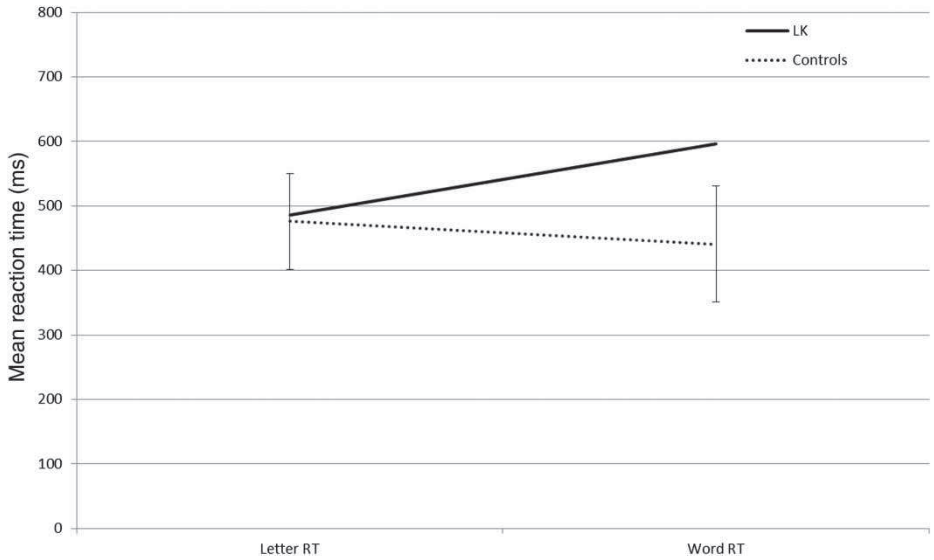

Figure 3. *Reaction times (RTs) in the naming task of Experiment 1A: patient L.K. vs. controls. Error bars indicate 2 standard deviations from the mean of the controls' RT. The standardized difference between L.K.'s two scores qualifies as a classical dissociation.*

the controls, RTs below 200 ms and above 900 ms were considered voice key errors (i.e., setting off the microphone too early or too late) and were removed from the data. For L.K., we removed all data points above or below 2.5 standard deviations of her mean RT, resulting in the removal of 3 data points for letters and 3 for words, comparable to the control group where, on average, 2.8 ($SD = 2.5$) letter trials and 2.4 ($SD = 2.7$) word trials were removed. L.K. performed the letter naming task first, as did half of the control subjects ($N = 11$).

Results

Neither L.K. nor controls made any errors in this task. In the control group, the mean RTs were significantly longer for single letters, $M_{\text{LetterRT}} = 476$ ms ($SD = 37$), than for words, $M_{\text{WordRT}} = 441$ ms ($SD = 45$), $t(20) = 4.94$, $p < .001$. Fifteen out of 21 subjects showed a significant word superiority effect in RTs, when their individual RTs for words versus letters were compared using a paired-sample t-test (all $p < .05$). This was not due to the greater number of trials in the word condition: The RT advantage for naming words was slightly smaller but still significant even when analysing only the first 50 word trials, $\text{M}_{\text{50WordRT}} = 447$ ms ($SD = 48$), $t(20) = 3.75$, $p = .001$. The correlation between RT for letters and words was $r = .74$.

L.K.'s mean RT for letters was 486 ms ($t = -0.26$, $p = .40$; Crawford & Howell's test), well within the range of the normal controls, while her mean RT of 596 ms for words was significantly elevated compared to the control group mean ($t = -3.37$, $p = .002$; Crawford & Howell's test). Interestingly, L.K. was significantly slower at naming words than letters, thus showing the opposite pattern to that of controls. Indeed, L.K.'s pattern of performance corresponds to a (putatively) classical dissociation, when analysed using Crawford and Garthwaite's (2007) methods: She was well within the normal range for letter naming and significantly outside the normal range for word naming, and the standardized difference between her two scores is significant ($p = .0002$). See Figure 3.

Experiment 1B: Letter and word perception

To evaluate the visual processing component in letter and word recognition, we presented the

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same stimuli as those in Experiment 1A in a single item report task with brief, masked presentation at a range of different exposure durations. We have previously used the same paradigm for testing letter and digit perception in pure alexic patients (Starrfelt, Habekost & Gerlach, 2010; Starrfelt, Habekost, & Leff, 2009) and normal participants (Starrfelt & Behrmann, 2011).

Method

Single stimuli were flashed briefly at the centre of the screen and then masked. Letters and words were presented in separate blocks of 160 trials. In total, subjects completed 320 trials per condition, and the first and second blocks for each stimulus type were preceded by 30 and 15 practice trials, respectively. L.K. performed this task in an ABBA order (letters–words–words–letters), and, for the controls, the order of tasks was counterbalanced (six controls performed the task in the same order as L.K.). In each trial, a single stimulus was chosen randomly and was presented for one of eight randomly intermixed exposure durations. For the controls, these exposures were: 6 ms, 12 ms, 19 ms, 25 ms, 31 ms, 37 ms, 62 ms, and 81 ms. The stimulus was terminated by a pattern mask shown for 500 ms. Participants were instructed to make an unspeeded report of the stimulus, if they were "fairly certain" of its identity (to reduce guessing). Responses were recorded by the experimenter. To ensure foveal presentation, participants were required to focus on a centrally placed cross and then to initiate the trial by pressing the right mouse button. Performance in the experiment was modelled individually by TVA using a maximum likelihood fitting procedure (see General Method). This resulted in separate parameter estimates for visual processing speed (C) and threshold of conscious perception (t_0) for each participant, separately for letters and words. L.K. was tested with a set of exposure durations that was individually adapted to her performance level and thus not entirely identical to that for the controls. L.K. performed the same number of trials as controls (320) per stimulus type, including seven exposure durations (12 ms, 19 ms, 25 ms, 31 ms, 37 ms, 62 ms, 81 ms), which were directly comparable to those for the control group, and two exposure durations (44 ms and 100 ms), which were not. In the 12-ms and 44-ms conditions, she received 20 trials (for letters and for words), while for the other exposures she received the same number of trials as the controls (40 per stimulus type). L.K.'s slightly different total set of exposure conditions does not preclude a direct comparison to the TVA parameters in the control group, as TVA parameters generalize across different sets of exposure durations, assuming they span the relevant time interval from floor to ceiling performance (hence the individual titration for L.K.): When analysing only the data from the seven exposure durations that were used for both L.K. and controls, L.K.'s TVA parameter estimates were almost identical to those reported in the main analysis. One outlier data point was removed from the analysis of L.K.'s data: a single correct response at 12 ms in the letter condition. Because L.K. had a zero score at 19 ms and only one correct report at 25 ms (out of 80 total trials in these two conditions), this single observation at 12 ms was deemed to be a "lucky guess" in an exposure condition that was clearly below L.K.'s perception threshold.

Results

In the control group, the mean accuracy score across the seven exposure durations comparable to L.K.'s was .58 ($SD = .14$) for letters and .73 ($SD = .09$) for words. The difference between the two mean scores was highly significant ($p < .0005$) with performance with words clearly superior to that with letters. Examination of individual exposure durations revealed that words were processed significantly better than letters ($p < .05$) at all exposure durations except the shortest (6 ms and 12 ms) and the longest (81 ms), where there were floor and ceiling effects for both letters and words. The correlation between accuracy for letters and words was $r = .72$ in controls. For L.K., the mean scores for the same seven exposure conditions was .28 for letters and .29 for words, both significantly impaired compared to the control group ($t = -2.09$, $p = .025$, and $t = -4.78$, $p < .0005$, respectively; Crawford &

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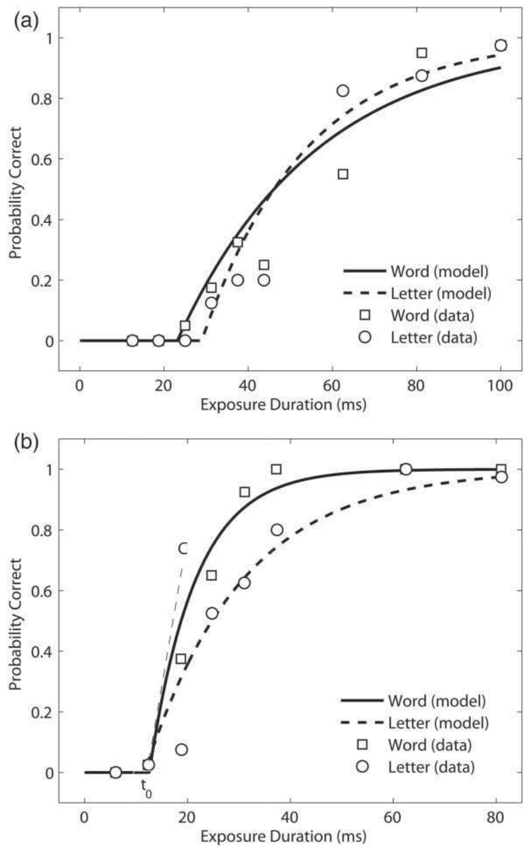

Figure 4. *Performance in the visual perception task of Experiment 1B: (a) patient L.K. versus (b) a representative control participant. Observed scores are marked by circles (letters) and rectangles (words), and the theory of visual attention (TVA) fit to the data is represented by solid curves. For the control participant, visual processing speed* C *and the perceptual threshold* t_0 *are shown for word stimuli.*

Howell's test). Although L.K. actually performs numerically on the same level with both stimulus types, this lack of a word superiority effect qualifies as a strong dissociation ($p = .003$, Crawford & Garthwaite's test): Her deficit in perceiving words is significantly larger than her deficit in letter perception, when compared to controls.

A subsequent TVA analysis of the data specified performance into two parameters: the perceptual threshold, t_0, and visual processing speed, C. In the control group, the average perceptual threshold was 14 ms ($SD = 7.1$) for letters and 12 ms ($SD = 3.3$) for words. The two mean values were not significantly different. For single letters, L.K.'s perception threshold was estimated at 29 ms, and for words it was 23 ms. Both t_0 values were significantly higher than the control group mean (letters: $t = -2.06$, $p = .026$; words: $t = -3.26$, $p = .002$; Crawford & Howell's test). Concerning visual processing speed C, the control group had a mean value of 68 items per second ($SD = 24$) for letters and 114 items per second ($SD = 40$) for words. The difference between the two mean values was highly significant ($p < .001$). In comparison, L.K.'s C values for letters and words were 40 and 30 items/second, respectively. Visual processing speed for letters ($t = -1.14$, $p = .13$; Crawford & Howell's test) was not significantly below the control group mean but the speed for word processing diverged significantly from that of the controls ($t = -2.05$, $p = .027$; Crawford & Howell's test). There were no dissociations between L.K.'s two t_0 values ($p = .16$; Crawford & Garthwaite's test; the correlation in the control group was $r = .42$) nor between the two C values ($p = .22$; Crawford & Garthwaite's test; the correlation in the control group was $r = .36$). See Figure 4 for an illustration of how L.K.'s accuracy scores for letters and words developed as a function of exposure duration, compared to that of a typical control participant.

Summary of Study 1

An overview of results from Study 1 is presented in Table 1. On a group level, the control participants showed a significant word superiority effect in both naming (Experiment 1A) and perception (Experiment 1B). In the single item report task, controls scored significantly higher with words than letters at all exposures between floor and ceiling performance, and TVA analysis related this word superiority effect specifically to visual processing speed (parameter C). Critically, this pattern was not found in L.K. Her naming of words in Experiment 1A was significantly slower than that of controls, whereas naming of letters was within the normal range ("word inferiority"). In contrast, L.K.'s performance on the visual perception task in Experiment 1B can best be described as "word–

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Table 1. *Study 1 results*

Experiment	*Measure*	*Controls*	*L.K.*
Experiment 1A	Letters: latency (ms)	476 (37)	486
		≠	≠
	Words: latency (ms)	441 (45)	596[a]
Experiment 1B	Letters: accuracy	.58 (.14)	.29[a]
		≠	≠
	Words: accuracy	.73 (.09)	.30[a]
	Letters: t_0 (ms)	14 (7.1)	29[a]
	Words: t_0 (ms)	12 (3.3)	23[a]
	Letters: C (items/s)	68 (24)	40
		≠	
	Words: C (items/s)	114 (40)	30[a]

Note: C = speed of visual processing; t_0 = perceptual threshold. For the control group, a ≠ sign between rows indicates significant differences in performance between letters and words. For L.K., ≠ between rows indicates the presence of a statistically significant dissociation (strong or classical) in performance between letters and words.
[a]Abnormal scores by L.K.

letter equality": Her mean scores in the two conditions were roughly the same, and both scores were significantly reduced relative to controls. However, because of the word superiority pattern in the control group, there was a strong dissociation between the two deficits (i.e., the word deficit was relatively larger). A TVA analysis of the results showed that L.K.'s perception thresholds for letters and words were both significantly elevated. L.K.'s visual processing speed for words was significantly reduced, while her visual processing speed for letters was nonsignificantly lower than that of controls.

An interesting finding was that, whereas the normal word superiority effect was absent in L.K., her similar performance with individual letters and three-letter words indicates that she is capable of parallel processing of letters visually, a finding that contrasts with the (supposedly) serial processing pattern evident in her WLE.

STUDY 2: PATIENTS E.L., G.B., AND S.H.

To test the generality of the findings obtained from patient L.K., we tested three additional patients with pure alexia with the same tasks. These patients were tested in the US and had English as their first language. Consequently, the experiments were translated into English, and, for the word conditions, new stimuli were generated. Although this approach makes direct comparisons of scores between Study 1 and Study 2 difficult, the similarity of the performance patterns across the two languages may be informative.

Case descriptions

Patient E.L.

E.L. is a right-handed female who was 64 years old at the time of this investigation (April 2013). In April 1996, she was admitted to hospital after suffering two embolic events that caused blurred vision, right arm weakness, and slurred speech. Her speech and language difficulties and the arm weakness recovered rapidly. E.L. was diagnosed as having bacterial endocarditis. Before this incident, E.L. worked as a special education teacher. A 3-T MRI scan in 2009 shows a left posterior cerebral artery infarct affecting the medial temporal lobe and occipital lobe (see Figure 5a). E.L. suffers from a right upper quadrantanopia with macular sparing. E.L. has corrected-to-normal vision (contact lens) on her right eye. E.L. has been described in detail in previous publications (e.g., Behrmann, Nelson, & Sekuler, 1998).

Patient G.B.

G.B. is a right-handed female, who was 72 years old at the time of this investigation (April 2013). She suffered a posterior cerebral artery (PCA) stroke in 2008, resulting in reading problems and an upper right quadrantanopia. Tested on the Boston Diagnostic Aphasia Examination (including Boston Naming Task) about 1 month following her stroke, she achieved 100% accuracy on tasks related to conversational and expository speech, auditory comprehension, and naming. On the reading tasks, she attained 100% accuracy on basic symbol recognition and word identification. As expected, she had decreased performance on the oral reading tasks, scoring only 66.7% (10/15) on basic word reading and 40% (2/5) on sentence

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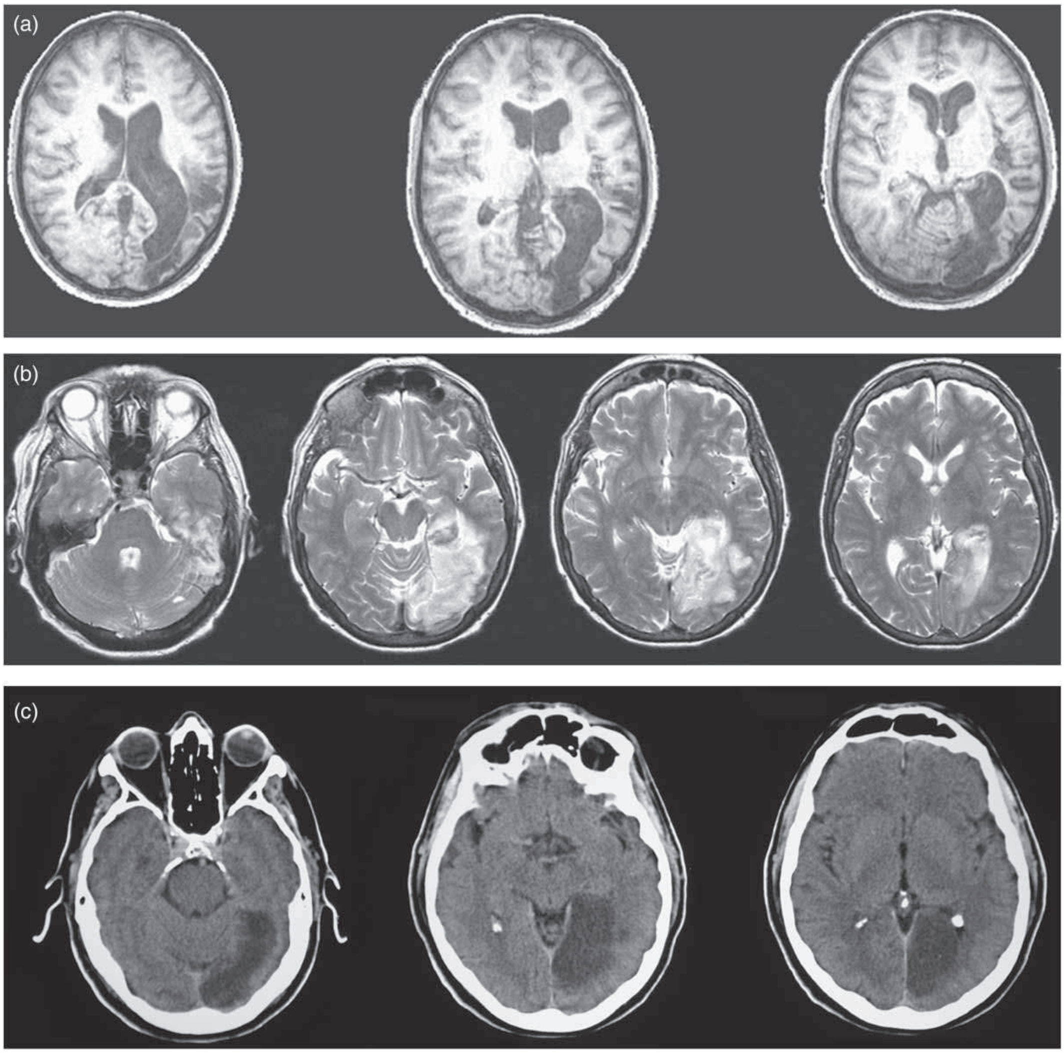

Figure 5. *Magnetic resonance imaging (MRI) scans of the lesions of patients (a) E.L., (b) G.B., and (c) S.H. Images are presented following radiological convention (left hemisphere depicted on the right).*

reading. On the writing section, she scored 100% on letter formation and motor facility, dictated words, and written picture naming. She scored 90.5% accuracy (19 of 21) on letter choice. These results are consistent with pure alexia. An MRI scan performed in 2011 shows a lesion affecting the posterior two thirds of the left temporal lobe and the inferior aspect of the left occipital lobe (see Figure 5b). The lesion measures approximately 9 cm in maximum anteroposterior diameter by 4.0–4.5 cm in maximum mediolateral diameter. G.B. has corrected-to-normal vision and wears bifocal glasses.

Patient S.H.

S.H. is a right-handed male who was 71 years old at the time of this investigation (April 2013). In July 2004, he experienced a sudden onset of right-sided visual loss, dizziness, and headache and was hospitalized with a right homonymous hemianopia.

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A 1.5-T MRI revealed a lesion affecting left temporo-occipital structures and the left thalamus, compatible with a left PCA infarct (see Figure 5c). Before his stroke, S.H. worked as an attorney. S.H. has corrected-to-normal vision (contact lenses on both eyes). He is red–green colour blind. Previous testing of S.H.'s reading and visual processing has been reported by Behrmann and Plaut (2012). In the current study, S.H. had to be tested in his own home, where lighting conditions were not as controlled as in the lab. The computer and screen, as well as screen distance, were the same as those for the other patients and controls.

Control participants

Eight healthy control participants (mean age: 64.3 years, *SD* = 4.6 years; 7 females) of either American (5) or English (3) nationality were included in Study 2. One participant was recruited in Pittsburgh, and the seven remaining participants were recruited in Copenhagen. Although now living in Denmark, all of these participants had English as their native language. None of the three patients in Study 2 differed significantly from the control group in terms of age (*ns*, Crawford & Howell's test). All control participants were right-handed and had normal or corrected-to-normal vision. The three patients and all control participants gave informed written consent according to the Helsinki Declaration to participate in the study. Approval was given by the Biomedical Research Ethics Committee in Copenhagen (KF 01–258988) for the controls and by the Institutional Review Board at the University of Pittsburgh (IRB# 0310066) and Carnegie Mellon University for the patients.

Background testing

Visual field test

We devised a computerized visual field test using E-prime software, building on a test originally devised and validated by Koaiva et al. (2012). We included a few additional stimuli towards the centre of the visual field so as to obtain a better estimate of central vision. A total of 32 positions ranging from 1 to 10° to either side horizontally and 1–5° to either side vertically were tested with white dots, while central fixation was controlled by a colour detection task (similar to the test devised by Kasten et al., 1999, which was used for the investigation of patient L.K.). All points were tested twice, so that the test ran in two blocks of 32 trials each. The subjects were instructed to press the space bar whenever a white dot appeared and whenever the fixation cross changed colour from red to green. Intertrial intervals varied randomly between 600 and 1100 ms from response to the next stimulus.

E.L. responded in 50% of the trials to each of the stimuli along the horizontal midline in the right hemifield and did not respond at all to two points about 8 degrees to the right of fixation in the upper and lower right quadrant, respectively. She responded consistently to all other stimuli, including the points presented in the central right visual field. G.B. showed signs of an upper right quadrantanopia with foveal sparing and sparing of the horizontal midline. S.H. missed two stimuli on the right side once, which may, in his case, have been a result of the lighting conditions under testing (see above), and we interpret his results as consistent with a sparing of the central 10 degrees of vision. In light of the sparing of the central field in all three patients, all stimuli in Experiments 2A and 2B were shown foveally.

Word reading

We used the same reading task as that of Starrfelt, Habekost, and Leff (2009) with 75 words of 3, 5, and 7 letters (25 for each word length) matched for frequency and *N*-size. Vocal RTs were measured using a voice key. Errors were recorded by the experimenter, and error trials were excluded from the RT analysis. The controls made an average of 0.2 reading errors (range 0–1) and 0.9 voice key errors (range 0–3). The patients made 5 (E.L.), 1 (G.B.), and 0 (S.H.) reading errors and 4 (E.L.), 0 (G.B.), and 2 (S.H.) voice key errors.

The mean naming RT of the controls was 472 ms (*SD* = 49 ms). The three patients had markedly higher mean RTs: 2085 ms (E.L.), 3316 ms (G.B.), and 3018 ms (S.H.). All were significantly different

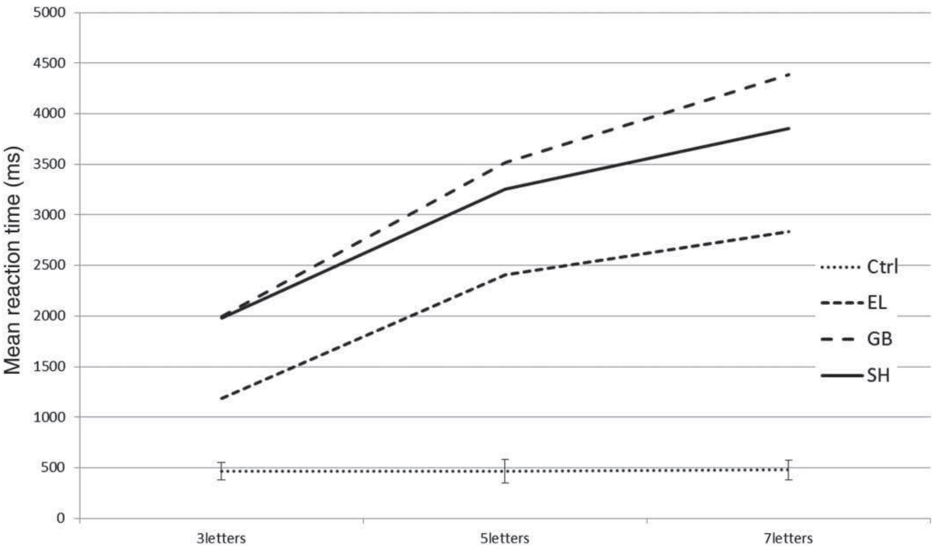

Figure 6. *Word length effect in patients G.B., E.L., and S.H. compared to control participants. Reaction time (RT) is plotted as a function of word length. Error bars for the controls represent* ±2 *standard deviations.*

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from the control group mean ($p < .001$; Crawford & Howell's test). Analysed by standard linear regression, none of the control participants showed a significant word length effect, while this was the case for all three patients. For E.L., the WLE was 419 ms/letter [$r^2 = .4$, $F(64, 1) = 41.8$, $p < .001$], for G.B. it was 596 ms/letter [$r^2 = .49$, $F(72, 1) = 68.4$, $p < .001$], and for S.H. it was 469 ms/letter [$r^2 = .59$, $F(71, 1) = 101.1$, $p < .001$]. See Figure 6 for an illustration of reading RTs and WLEs for the three patients compared to the control participants.

Stimuli and masks

In both experiments in Study 2, we used the same letter set as that in Study 1 and kept the font and size of the stimuli the same across paradigms. As the patients in this investigation were American, a new word list was created, which included 25 three-letter, high-frequency English words. Again, we ensured that no word could be predicted or guessed by identifying a single letter (see Appendix for stimuli and stimulus characteristics). The same order of tasks was used for all control subjects and patients: letter naming, word naming, and four blocks of the visual perception task in an ABBA (letter–word–word–letter) design. The letter condition featured 25 letters of the alphabet ("w" excluded). Masks were white-on-black pattern masks constructed of letter fragments, identical to those used in Study 1.

Experiment 2A: Letter and word naming

Method

The experimental design and procedure was the same as those in Experiment 1A except for the English word stimuli (see Appendix) and the fact that there were only 50 word trials in Experiment 2A (compared to 100 in Experiment 1A). RT analysis was based on correct responses only.

Results

The controls made no reading errors in this task. Patient E.L. and S.H. made 2 errors in the letter naming task, while in the word task, the patients made 5 (E.L.), 2 (G.B.), and 4 (S.H.) errors, respectively. In the control group, the mean RTs for single letters, $M_{\mathrm{LetterRT}} = 473$ ms ($SD = 42$

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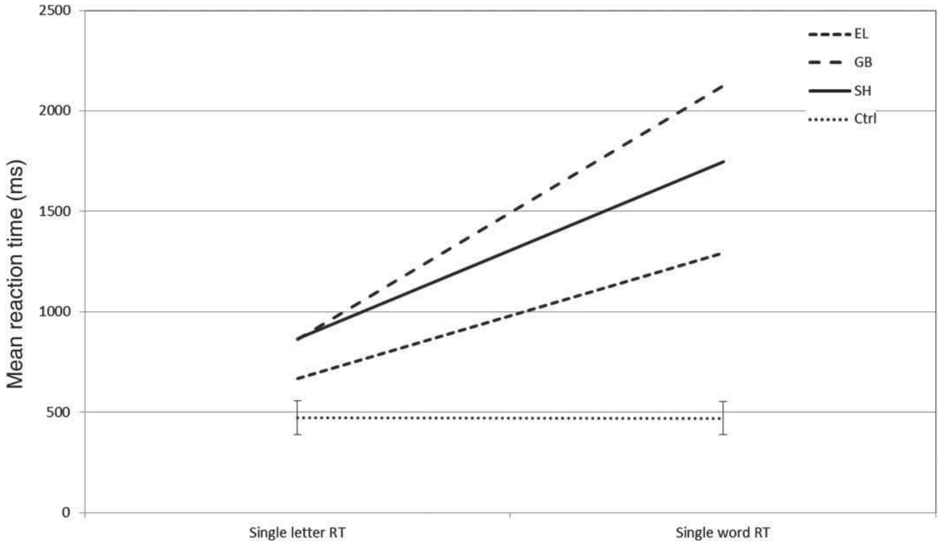

Figure 7. *Reaction times in Experiment 2A for single letter and single word naming for patients G.B., E.L., and S.H. versus controls. Error bars for the controls represent* ±2 *standard deviations.*

ms) were not significantly different from those for words, $M_{\text{WordRT}} = 471$ ms ($SD = 52$ ms; $p = .90$). The mean RT of each patient for letters was 668 ms (E.L.), 861 ms (G.B.), and 866 ms (S. H.). All three values were significantly higher than the control group mean ($t = -4.38$, $p = .002$, $t = -8.71$, $p < .0005$, and $t = -8.82$, $p < .0005$, respectively; Crawford & Howell's test). For words, the increase in mean RTs was even more pronounced: 1295 ms (E.L.), 2126 ms (G.B.), and 1749 ms (S.H.). All values were extremely deviant from the control group mean ($t = -14.94$, $t = -30.0$, and $t = -23.17$, respectively, $p < .0005$ in all cases; Crawford & Howell's test). Importantly, all three patients fulfilled the criteria for a strong dissociation between the two tasks: They performed significantly better with letters than with words with reference to controls ($p < .001$ in all cases, Crawford & Garthwaite's test; the correlation in the control group was $r = .76$). See Figure 7.

Experiment 2B: Letter and word perception

Method

The experimental design was the same as that in Experiment 1B except for the (English) word stimuli (see Appendix). The set of exposure durations was slightly different: Longer exposure durations were included because of the patients' higher age: 24 ms, 35 ms, 47 ms, 59 ms, 71 ms, 82 ms, 94 ms, 106 ms, 117 ms, and 129 ms. Controls and patients were tested with the same set of exposures and performed 2 × 20 trials at each exposure condition (randomly intermixed). The testing was done in four blocks of 100 trials each, in an ABBA (letter–word–word–letter) fashion, the same order for all participants.

Results

In the control group, the mean accuracy across the 10 exposure conditions was .83 ($SD = .04$) for letters and .93 ($SD = .03$) for words. The difference between the two mean scores was highly significant ($p = .00002$); performance was significantly better with words than with letters. Looking at individual exposure durations, this word superiority effect was significant at the three lowest exposure durations (24 ms, 35 ms, and 47 ms: $p = .00002$, $p = .000001$, and $p = .02$, respectively), but not at longer exposures, where controls performed at ceiling levels with both letters and words.

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The correlation between accuracy for letters and words was $r = .64$.

In the letter condition, the mean scores for the patients were .62 (E.L.), .6 (G.B.), and .78 (S.H.). E.L. and G.B. were significantly below the control group mean ($t = -4.95$, $p = .001$, $t = -5.42$, $p < .0005$, respectively; Crawford & Howell's test), but interestingly S.H.'s mean score was within normal variation ($t = -1.18$, $p = .14$; Crawford & Howell's test). For words, the patients' mean scores were .6 (E.L.), .49 (G.B.), and .47 (S.H.). All scores were extremely deviant from the control group mean ($t = -10.37$, $t = -13.83$, and $t = -14.46$, respectively; $p < .0005$ in all cases; Crawford & Howell's test). Further, the mean scores for letters versus words were significantly dissociated for all three patients: There was a strong dissociation for E.L. ($p = .014$), a strong dissociation for G.B. ($p = .003$), and a (putatively) classical dissociation for S.H. ($p < .000005$). In contrast to the control participants, who showed a word superiority effect, all patients performed better with letters than with words.

A TVA analysis of the raw data specified performance into two parameters: the perceptual threshold, t_0, and visual processing speed, C. In the control group, the average t_0 value was 25 ms ($SD = 3.8$ ms) for letters and 15 ms ($SD = 5.9$ ms) for words. The two mean values were significantly different ($p = .0005$, paired t-test), reflecting a word superiority effect. The correlation between the two t_0 values was $r = .64$. For single letters, the t_0 values of the three patients were estimated at 31 ms (E.L.), 43 ms (G.B.), and 24 ms (S.H.). The t_0 value of G.B. was significantly different from the control group mean ($t = -4.47$, $p = .001$; Crawford & Howell's test). For single words, the t_0 values of the three patients were estimated at 20 ms (E.L.), 31 ms (G.B.), and 35 ms (S.H.). The t_0 values of G.B. and S.H. were significantly different from the control group mean ($t = -2.56$, $p = .019$, and $t = -3.20$, $p = .008$, respectively; Crawford & Howell's test). S.H. fulfilled the criteria for a (putatively) classical dissociation: a normal t_0 value for letters, an abnormal t_0 value for words, and a standardized difference between the two scores that was significantly different from that of controls ($p = .002$; Crawford & Garthwaite's test). The other two patients did not show significant dissociations between their t_0 values for words and letters.

Concerning visual processing speed, C, the control group had a mean value of 86 items per second ($SD = 26$) for letters and 108 items per second ($SD = 26$) for words. The difference between the two mean values did not reach significance ($p = .10$). The correlation between the C values for letters and words was $r = -.54$. In comparison, the three patients' C values for letters were 30 (E.L.), 45 (G.B.), and 51 (S.H.) items per second. Only E.L.'s C value for letters was significantly below the control group mean ($t = -2.03$, $p = .041$; Crawford & Howell's test). For words, the three patients' C values were 19 (E.L.), 18 (G.B.), and 19 (S.H.). All three values were significantly below the control group mean ($t = -3.23$, $p = .007$, $t = -3.26$, $p = .006$, and $t = -3.23$, $p = .007$, respectively; Crawford & Howell's test). None of the patients' profiles, however, fulfilled Crawford and Garthwaite's (2007) statistical criteria for a dissociation between their C values for letters and words. See Figure 8 for the performance of all three patients in the two conditions of Experiment 2B compared to a typical control participant.

Comparing the patients' results in Experiments 2A and 2B, patient S.H.'s performance qualified as a (putatively) classical dissociation ($p = .002$, Crawford & Garthwaite's test; the correlation in the control group was $r = -.11$): He was significantly impaired in letter naming (2A), but performed within normal limits in letter perception (2B), and the standardized difference between his two scores was significant. No other comparisons between performance in the two experiments qualified as dissociations.

Summary of Study 2

An overview of the results from Study 2 is presented in Table 2. The classical word superiority effect found in Study 1 was replicated in the English control participants in the accuracy task (Experiment 2B), but was reflected mainly in

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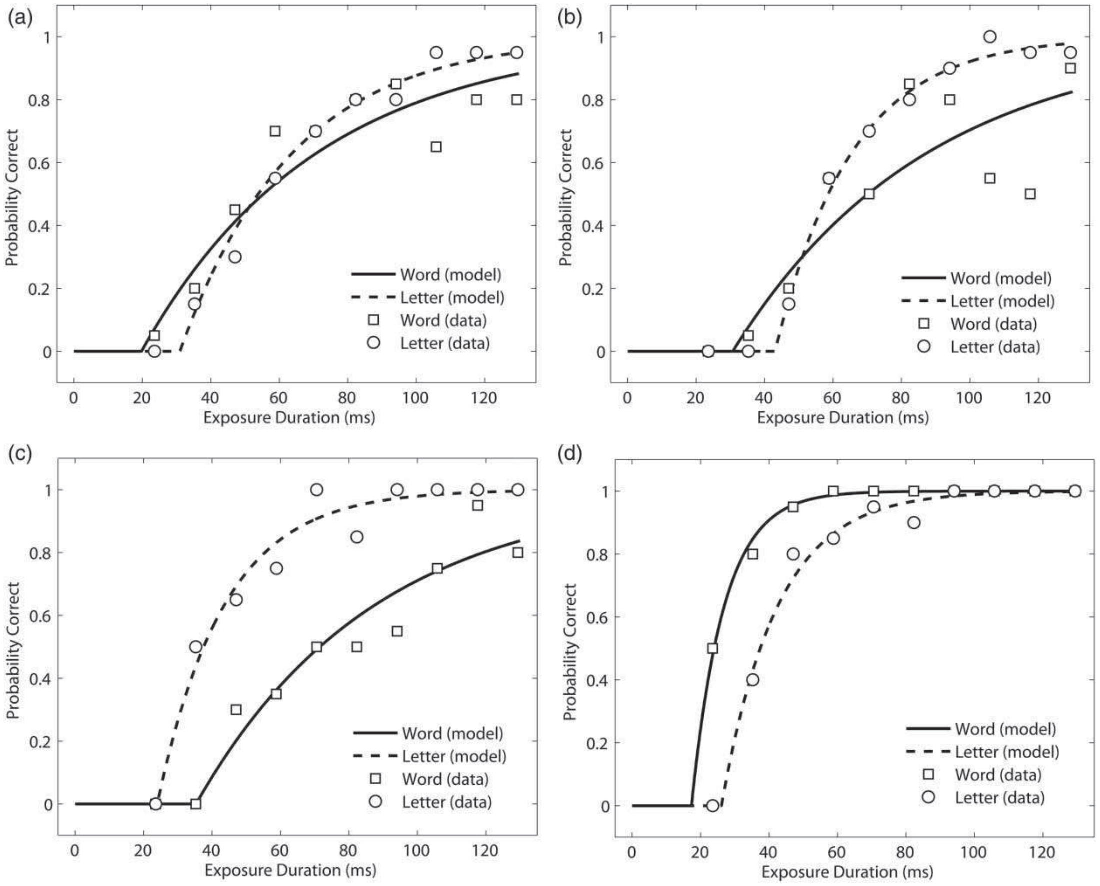

Figure 8. *Performance in the visual perception task of Experiment 2B: patients (a) E.L., (b) G.B., and (c) S.H. versus (d) a representative control participant. Observed scores are marked by circles (letters) and rectangles (words), and the theory of visual attention (TVA) fit to the data is represented by solid curves.*

perceptual threshold rather than visual processing speed. In contrast to Study 1, no WSE was observed in naming RTs in these controls (Experiment 2A). The discrepancies to the results of Study 1 may be related to several factors: They may partly be explained by the fact that different words (in English) were used, and possibly also effects of random statistical noise due to the smaller size of the control group in Study 2.

In Experiment 2A, all three patients were significantly slower than controls in naming both letters and words. Notably, the naming deficit was markedly larger with words for all patients (a strong dissociation between the performance with letters and words was found in each case). This general word inferiority pattern was also found in Experiment 2B, where significant dissociations between letter and word performance were also found in all three patients. As expected, E.L. and G.B. were also significantly impaired with perception of single letters, but, interestingly, S.H. performed within normal limits for letters, though he was clearly impaired with words (a classical dissociation was found for both mean accuracy scores and t_0 values). To our knowledge, this is the first clear demonstration of a patient with pure alexia who shows intact visual perception of single letters on such a demanding task. Remember that S.H., in contrast to the other

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Table 2. *Study 2 results*

Experiment	*Measure*	*Controls*	*E.L.*	*G.B.*	*S.H.*
Experiment 2A	Letters: latency (ms)	473 (42)	668^{a}	861^{a}	866^{a}
			≠	≠	≠
	Words: latency (ms)	471 (52)	1295^{a}	2126^{a}	1749^{a}
Experiment 2B	Letters: mean accuracy	.83 (.04)	.62^{a}	.60^{a}	.78
		≠	≠	≠	≠
	Words: mean accuracy	.93 (.03)	.60^{a}	.49^{a}	.47^{a}
	Letters: mean t_0 (ms)	25 (3.8)	31	43^{a}	24
		≠			≠
	Words: t_0 (ms)	15 (5.9)	20	31^{a}	35^{a}
	Letters: C (items/s)	86 (26)	30^{a}	45	51
	Words: C (items/s)	108 (26)	19^{a}	18^{a}	19^{a}

Note: C = speed of visual processing; t_0 = perceptual threshold. For the control group, a ≠ sign between rows indicates significant differences in performance between letters and words. For E.L., G.B., and S.H., ≠ between rows indicates the presence of a statistically significant dissociation (strong or classical) in performance between letters and words.

[a]Abnormal scores by patients.

patients and controls, performed the tasks in broad daylight, which should if anything make the task more challenging for him than for the others, and still he is well within the normal range for letter perception. This is even more interesting when considering S.H.'s significantly elevated RTs in letter naming. His performance in Experiments 2A and 2B qualified as a (putatively) classical dissociation: Whereas his perception of brief, masked letters was within normal limits, his naming RT was significantly elevated. This raises the question of whether the deficit affecting his naming time for letters and his perception and naming of words is the same, or arises at different levels.

GENERAL DISCUSSION

Aiming to investigate the relationship between letter and word processing in pure alexia, we conducted two experiments: a vocal naming task (Experiments 1A and 2A), and a visual perception task (Experiments 1B and 2B) with four pure alexic patients. In a recent study of young normal subjects, using the same two experimental paradigms, we observed a significant word superiority effect in both naming and visual processing (Starrfelt, Petersen, & Vangkilde, 2013).

The current experiments produced several interesting findings: First, none of the patients showed a word superiority effect in naming or in visual perception. In the naming task, all patients showed significantly higher RTs for words than single letters, a pattern that deviated significantly from controls who either showed faster responses for words (Study 1), or equal RTs for words and single letters (Study 2).[1] All patients were more impaired in naming words than single letters, and all patients showed statistically significant dissociations (as evaluated by Crawford et al.'s methods) between their performance in the letter and word naming tasks.

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[1] It should be noted here that very few experimental studies have investigated the WSE in the context of RTs to unmasked words. Following Cattell's (1886) original observation of faster RTs to words than letters, this finding has received relatively little attention compared to the corresponding effect in accuracy (e.g., Reicher, 1969; Johnston, 1981; Seidenberg & McClelland, 1981; Wheeler, 1970). Thus, although the effect on RTs was robust in our Danish control group, the circumstances (subject, age, language, word characteristics, word lengths, etc.) under which the word superiority effect can be observed in response time remains to be determined (see Starrfelt, Petersen, & Vangkilde, 2013).

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The same lack of word superiority was observed in the pure alexic patients in the visual perception experiment (Experiments 1B and 2B). Here, both control groups showed a clear and significant word superiority effect in overall accuracy. L.K., who had the mildest pure alexia, showed what can best be described as "letter–word equality" in this experiment: Her overall accuracy across exposures was essentially equal for words and letters, and it was significantly impaired for both types of stimuli. However, as the controls showed a word superiority effect in this task, L.K.'s equal performance with letters and words statistically qualified as a strong dissociation. Patient E.L. showed the same pattern as L. K.: "letter-word equality" with significantly poorer performance with words than letters when compared to the controls' words superiority effect. For G.B. and S.H., the pattern of performance may be described as "word inferiority"; they performed significantly worse with words than with letters in terms of overall accuracy in the perception experiment. Also striking here is that S.H.'s scores in the letter perception task actually fell within the range of the normal controls, and his "word inferiority effect" constitutes a statistically significant classical dissociation. This finding is particularly intriguing, as S.H.'s RTs in the letter naming task (2A) was significantly elevated compared to the same controls. Indeed, S.H.'s performance with single letters across the two experiments also statistically qualifies as a classical dissociation.

To sum up, all patients showed an abnormal pattern of performance: Word naming and word perception were more severely affected than letter naming and perception for all patients. No patient showed a word superiority effect in either experiment. In addition, one patient (S.H.) was within the normal range in visual letter perception, while being severely impaired at all the other measured aspects of letter and word processing.

From word superiority to word inferiority

An abnormal feature of all four patients was a deviation from the normal word superiority effect towards a pattern that can be termed "word inferiority". The effect was smallest in patient L.K., who had the mildest form of pure alexia of the four patients (as measured by the size of WLEs and word naming RTs). L.K. took on average 110 ms extra to name words compared to letters, and in the visual perception task, her performance was close to identical for letters and words. Compared to the word superiority effects in the control group, dissociations between letter and word performance could be shown for L.K. in both experiments, but the effects were relatively minor. The word inferiority effects in the three patients of Study 2, who had more severe forms of pure alexia than L.K., were more pronounced. This was especially the case in the naming task, where these patients took about 600–1200 ms longer to name words than letters. In the perception experiment, patient E.L. scored approximately equally with letters and words, but compared to the normal word superiority effect, there was a dissociation between the magnitude of her deficits in letter and word perception. Both patient G.B. and patient S.H. were clearly worse at perceiving words than letters, which was also reflected in significant dissociations between word and letter performance.

The findings across our four patients suggest that word inferiority (or in milder cases, a lack of word superiority) is a general feature of pure alexia, but this may depend in part on the experimental paradigms. Previous studies of the WSE in pure alexia have reported contradictory results: Some studies report a significant WSE (Bub, Black, & Howell, 1989; Reuter-Lorentz & Brunn, 1990; Starrfelt, Gerlach, et al., 2013), while others do not (Behrmann, Black, & Bub, 1990; Kay & Hanley, 1991; Starrfelt, Habekost, & Gerlach, 2010). Commonly, WSE experiments are designed either as forced choice tests (did an A appear in the presented stimulus?) or as free report tests (report as many letters as possible from the presented stimulus; see e.g., Johnston, 1981), and there are some indications that the choice of paradigm may affect the performance in alexic patients (Bowers, Bub, & Arguin, 1996). However, few patients have been investigated using the same methods, and results are therefore hard to compare between studies. None of these previous studies has used a paradigm similar to

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ours, and none has used naming RTs or accuracy of whole word perception as the dependent measure. The WSE is typically investigated using longer words than in the current study (four letters or more). It is curious that even though we aimed to devise a very simple WSE experiment, "look at a short, simple word, say what it was", we seemed to have developed a task that is very difficult for pure alexic patients.

The word superiority effect was one of the driving forces in the development of the interactive activation model of visual word processing (IAM; McClelland & Rumelhart, 1981). In this model, word recognition is achieved through processing on three interactive levels, where activation on higher levels (i.e., word representations) can strengthen or inhibit activations on the letter level. These feedback connections are important in explaining the word superiority effect, as this top-down activation of letters in words renders them more active than does bottom-up activation alone (which is more likely to be the case when the stimulus is a single letter or a string of unrelated letters). An explanation for the lack of a WSE that we observe in our patients, then, may be a failure of the bottom-up signal from the stimulus word to engage top-down activation and inhibition of letters from the word level. Testing specifically for such an impairment in top-down processing is challenging, but would be an important goal for future studies, as the relative importance of bottom-up versus top-down processing in visual word recognition both in normal subjects and in patients with pure alexia is a matter of great controversy (Dehaene & Cohen, 2011; Price & Devlin, 2011).

A dissociation between letter perception and letter naming: Patient S.H.

A long-standing debate in pure alexia research concerns whether the basic deficit is related to visual processing of individual letters, or only arises with letter arrays (e.g., Behrmann & Shallice, 1995; Farah, 2004; Kinsbourne & Warrington, 1962). Behrmann, Plaut, and Nelson (1998) found "no single subject for whom letter recognition is definitively normal" (p. 23) in their review of the literature, and in a more recent review it was also concluded that a clear demonstration of normal letter processing in pure alexia is still lacking (Starrfelt & Behrmann, 2011). In the present study, we found patient S.H. to have intact visual letter perception, in terms of both overall accuracy and processing speed, while his response times in letter naming are significantly elevated. S.H.'s results statistically qualifies as a classical dissociation between relatively preserved letter perception (1.25 *SD*s below the control mean, which is within the normal range) and severely impaired letter naming (an impressive 9.4 *SD*s below the normal mean). How, then, can we explain his elevated response times in letter naming, and how these do (or do not) relate to his alexia: his impaired visual perception and naming of words.

Starting with the question of normal letter perception, one of the few pure alexic patients previously reported to show letter naming RT within a normal range was patient F.K. studied by Rosazza, Appolonio, Isella, and Shallice (2007). His RTs in naming both letters and digits were within the normal range compared to an age matched control-group, as was his accuracy in a test of rapid letter identification, while his word reading was impaired. He also had other visual deficits, for instance in an object decision task, a pattern that may have a parallel in S.H., who in addition to his alexia is also impaired in face perception (Behrmann & Plaut, 2012). Rosazza et al. (2007) suggested that F.K.'s reading deficit was on the level of integrating letters into letter groups or words and suggested that such a deficit in the absence of problems in single letter identification, was enough to cause pure alexia. It seems that such an integration deficit would not be sufficient to explain S.H.'s pattern of performance, as his single letter naming (which obviously demands no integration of letter groups) is also affected.

Another pure alexic patient showing seemingly intact visual letter processing, is patient R.O.C. reported by Warrington and Langdon (1994, 2002). R.O.C.'s perceptual threshold for letter recognition was 35 ms (determined by a staircase procedure for recognizing 10 different, masked letters:

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The mean exposure necessary for correct identification was taken as the threshold). This performance was at the same level as that of a nonalexic control patient, but no normal controls were tested (Warrington & Langdon, 1994). Interestingly, R. O.C. was able to name words when letters were presented sequentially, and the exposure duration of the stimulus enabled explicit naming, but when the patients had to perform a simultaneous articulatory suppression task, letter-by-letter reading was hampered for the pure alexic patient. This led the authors to conclude that R.O.C.'s reading deficit was on a lexical (postperceptual) level and that overt letter naming was needed for him to recognize words. This explanation also does not seem to hold for patient S.H., who did not spell words out loud during reading and indeed showed a deficit in overt naming of single letters, but not in visual processing of the same stimuli.

Shallice (1988) reported a correlation between reading speed and the accuracy of single-letter identification in a group of eight letter-by-letter readers, which suggests a strong association between the two processes. However, others have described patients with fairly similar letter recognition patterns who nevertheless show very different performance in word recognition (Hanley & Kay, 1996). Our study seems to complicate matters further, as we find dissociations not only between letter and word processing within the same paradigm (naming or perception task), but also between letter perception and letter naming. Even if we assume that a postperceptual (lexical or naming) process is affected in S.H., it is thought provoking that he does not seem able to exploit his intact visual perception of single letters in the visual perception task with words.

If we accept that S.H.'s visual letter processing is indeed unimpaired, it seems that the deficits observed in letter and word reading may not be causally connected in the way that impaired single letter processing is the cause of the word reading deficit in pure alexia. The fact that the deficit in word processing is disproportionally worse that in single letter processing in all four patients seem to suggest that the deficit observed in word reading may be explained by additional factors.

CONCLUSION

Aiming to explore the relationship between reading and recognition of words and single letters in pure alexia, we examined the word superiority effect across two tasks: naming and visual perception in four pure alexia patients. Word naming and word perception were more severely affected than letter naming and perception for all patients, and the word processing deficit increased with the severity of pure alexia. No patient showed a word superiority effect in either experiment, but the relationship between the patients' abilities for letter and word processing was not straightforward. One patient (S.H.) was within the normal range in visual letter perception, while being severely impaired in letter naming as well as word processing. The same pattern was evident, although less clearly, in the other patients; they were all disproportionally impaired with words compared to single letters, when compared to normal controls. This suggests that the reading deficit in these cases of pure alexia cannot be reduced to an impairment in visual processing of single letters and implies that their abnormal word processing must be explained by additional impairments.

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APPENDIX

Word stimuli and attributes

Study 1. Danish word stimuli

All words are high-frequency Danish words, with high neighbourhood size. At least two neighbour words were included in the list for all stimuli, thus making it necessary to process at least two and for most words all three letters in the word to identify it correctly.

Stimulus	*Freq. pr mill.*[a]	N_*size*[b]	*Neighbour stimuli in list*	
bag	266	25	3	bog; dag; tag
bog	107	23	2	bag; tog
dag	791	23	3	bag; dig; tag
den	9259	28	2	det; din
det	15,358	22	2	den; dit
dig	427	21	4	dag; din; dit; mig
din	267	24	4	den; dig; dit; min
dit	111	24	3	det; dig; din
fad	23	19	3	far; fod; mad
far	212	24	2	fad; for
fod	29	18	3	fad; for; mod
for	9336	22	3	far; fod; mor
han	4556	21	3	hun; kan; man
hun	2070	17	2	han; kun
kan	4058	15	3	han; kun; man
kun	970	14	2	hun; kan
mad	85	18	4	fad; man; med; mod
man	3146	17	4	han; kan; mad; min;
med	9204	15	2	mad; mod
mig	1123	18	2	dig; min
min	684	20	3	din; man; mig
mod	907	16	4	fod; mad; med; mor
mor	244	19	2	for; mod
tag	78	22	3	bag; dag; tog
tog	290	15	2	bog; tag
Mean	2544.04	20	2.8	
SD	4019.46	3.70	0.76	
Median	684	4	2	

[a] Bergenholtz (1992).

[b] Number of words in the Danish dictionary (www.ordnet.dk/ddo) differing from the target by only one letter. Values kindly calculated by the Danish Lexicographic Society.

Study 2. English word stimuli

All words are high-frequency English words, with high neighbourhood size. At least two neighbour words were included in the list for all stimuli, thus making it necessary to process at least two and for most words all three letters in the word to identify it correctly. The words were selected among the three-letter words included in the English Lexicon Project (Balota et al., 2007).

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Stimulus	*Freq. pr mill.*[a]	N_*size*		*Neighbour stimuli in list*
bag	125	20	5	ban,bat, beg, big, lag
ban	90	17	5	bag, bat, bin, pan, tan
bat	49	19	4	bag, ban, bet, pat
bed	239	13	3	beg, bet, led
beg	35	13	6	bag, bed, bet, big, leg, peg
bet	228	17	4	bat, bed, let, pet
big	1364	16	4	bag, beg, bin, pig
bin	121	17	3	ban, big, pin
lag	20	19	3	bag, lap, leg
lap	49	18	4	lag, lip, map, tap
leg	136	12	4	beg, lag, let, peg
let	1578	16	4	pet, leg, lit, pet
lip	25	15	3	lap; lit, pit
lit	41	14	3	let, lip, pit
pan	77	19	4	ban, pin, pat, tan
pat	130	22	4	bat, pan, pet, pit
peg	10	13	4	beg, leg, pet, pig
pet	113	21	5	bet, let, pat, peg, pit
pig	49	12	4	big, peg, pin, pit
pin	189	16	5	bin, pan, pig, pit, tin
pit	117	16	5	lit, pat, pet, pig, pin
tan	66	18	4	ban,pan, tin, tap
tap	87	19	3	lap, tan, tip
tin	90	17	4	bin, pin, tan, tip
tip	111	16	3	lip, tap, tin
Mean	205.56	16.60	4.00	
SD	378.88	2.68	0.80	
Median	90	17	4	

[a] Frequency estimates in this database are based on the HAL corpus (Lund & Burgess, 1996), which contains about 131 million words. Frequency per million was calculated by dividing total frequency by 131.